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A Methodological Framework for Evaluating the Environmental Performance of Large-Scale Sanitation Systems in Developing Countries

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A Methodological Framework for Evaluating the Environmental Performance of Large-Scale Sanitation Systems in Developing Countries

by

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Abstract

It is 2014 and approximately 40% of the world population still has no access to adequate sanitary toilets. For these 2.6 billion people the problem is not only finding a safe and dignified place to defecate, but also trying to combat deadly diseases associated with the exposure to pathogens in feces left on the ground or near waterways. Improving sanitation is not only favorable to health, but also promotes dignity, economic benefits and environmental conservation. Although there have been numerous efforts to improve sanitation systems in the developing world, adoption rates and long term use are relatively low due to poor understanding of the multiple requirements for sustaining such systems such as environmental conditions and cultural habits. Quantifying and comparing the costs and benefits of these systems to the environment is one step in better informing decision makers in large-scale development projects, and thus facilitating the selection of sustainable sanitation systems. The research conducted puts forth a method to assess and hierarchically classify large-scale systems based on their environmental performance and context. The proposed method provides structured steps of environmental assessment and multiple-criteria decision analysis to compare and contextually evaluate the environmental implications of large-scale systems. A case study on specific sanitation systems in Cap-Haïtien, Haiti was reviewed to demonstrate and evaluate the framework. The study compared the use of urine-diversion toilets coupled with a collection system that diverts waste to a compost facility versus flush toilets connected to sewer systems with either endpoint to waste stabilization ponds or discharged into the environment without treatment. Overall, the results from this study show that the alternative involving diverting waste to a compost facility was preferred to the other alternatives for large-scale sanitation systems for Cap-Haïtien, Haiti; although there are specific conditions where it might not be. Various scenarios and analysis were developed to help provide some perspective into the results and conclusions of the methodology and the modeled case study.

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List of Nomenclature

14DCB	1, 4-Dichlorobenzene
ABS	Acrylonitrile Butadiene Styrene
AHP	Analytic Hierarchy Process
ALO	Agricultural Land Occupation
BEA	British Environmental Agency
BFA	Box Flow Analysis
BOD	Biochemical Oxidation Demand
C2H6	Ethane
C3H8	Propane
CC	Climate Change
CI	Consistency Index
CO	Carbon Monoxide

CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CR	Consistency Ratio
DALY	Disability Adjusted Life Years
DINEPA	Direction Nationale De L' Eau Potable Et De l'Assainissement
EOL	End-Of-Life
EPA	United States Environmental Protection Agency
FD	Fossil Resource Depletion
FE	Freshwater Eutrophication
FRIDE	Foundation For International Relations And Foreign Dialogue
g	Grams
HDPE	High-Density Polyethylene Terephthalate
HT	Human Toxicity
IDEA	International Institute For Democracy And Electoral Assistance
IHSS	Institut Haïtien De Statistique Et d'Informatique
IR	Ionizing Radiation
ISO	International Standard Organization
kg	Kilograms
kWh	Kilowatt Hours
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory Assessment
LCIA	Life-Cycle Impact Assessment
m^2	Squared Meters
MCDA	Multiple-Criteria Decision Analysis
MDG	Millennium Development Goals
ME	Marine Eutrophication
MET	Marine Ecotoxicity
MFA	Material Flow Analysis
mg	Milligram
MRD	Mineral Resource Depletion
NaCl	Sodium Chloride
NaClO	Sodium Hypochlorite
NGO	Non-Governmental Organization
NH_4+	Ammonium
CH_4	Methane
NLT	Natural Land Occupation
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
OAS	Organization Of American States
OD	Ozone Depletion
PCE	Per-Capita Equivalents

PET	Polyethylene Terephthalate
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Formation
PP	Polypropylene
PPE	Personal Protection Equipment
PVC	Polyvinyl Chloride
RI	Random Consistency Index
SO_2	Suplhur Dioxide
SOIL	Sustainable Organic Integrated Livelihood
SO_x	Suplhur Oxides
SuSanA	Sustainable Sanitation Alliance
TA	Terrestrial Acidification
TET	Terrestrial Ecotoxicity
UDT	Urine-Diversion Toilet
ULO	Urban Land Occupation
UN	United Nations
UNEP	United Nations Environmental Programme
UNICEF	United Nations Children's Fund
USAID	United States Agency For International Development
WD	Water Depletion
WHO	World Health Organization
WSP	Waste Stabilization Ponds
WWTP	Wastewater Treatment Processes
λ	Eigenvalue

1. Introduction

Improving sanitation is not only favorable to health, but also promotes dignity, economic benefits and environmental conservation. This holds true especially for underdeveloped and developing regions of the world where around 2/3 of the population does not have access to sanitation facilities. Many different types of sanitation systems are available for implementation, and models vary greatly depending on the type of infrastructure and the technological expertise required to implement them. Although there have been numerous efforts to improve sanitation systems in the developing world, adoption rates and long term use are relatively low due to poor understanding of the multiple requirements for sustaining such systems such as environmental conditions and cultural habits. Quantifying the costs and benefits of these systems to the environment is one step in better informing decision makers in development projects, and thus facilitating the selection of sustainable sanitation systems. However, one of the main obstacles is the limited knowledge and available tools to adequately perform such analysis. The research conducted puts forth a method to assess and hierarchically classify large-scale sanitation systems based on their environmental performance and context.

2. Background

2.1 The burden of diarrhea

Diarrheal diseases have posed a major threat to human welfare since the beginning of civilization (Lim ML, 2004). The burden of diarrheal diseases to mankind can be observed by the high morbidity and mortality rates they cause, especially among children. Every year, 1.8 million people around the world die as a consequence of diarrheal diseases and consequent health complications (WHO, 2013). Globally, diarrheal diseases kill more children from ages 0 to 5 than malaria, AIDS, and measles combined (Liu et al., 2012). As such, diarrheal diseases are the fifth leading cause of illness and death and the second leading cause of death of children under the age of 5 (Balkema, Preisig, Otterpohl, & Lambert, 2002).

Aside from causing the death of millions every year, diarrheal disease can lead to a vast array of negative outcomes that can continue to affect people throughout their lives. In prolonged affliction, diarrhea during formative stages of childhood causes stunted growth and impaired cognitive development due to dehydration and malnutrition (Bowen A, 2012). The losses in productivity and the costs associated with healthcare due to diarrheal diseases can amount to millions of dollars annually (G. Hutton, Haller, & Bartram, 2007). Therefore, there are acute and chronic implications resulting from short and long term episodes of diarrhea with deleterious impacts to health and welfare.

Increasing supply and quality of water and sanitation, education, and vaccines are well-known interventions for the prevention and treatment of diarrhea. Yet a significant fraction of the world population do not have access to the methods to do so (WHO/UN, 2011). During the United Nation’s (UN) World Summit 2000, 185 countries pledged to meet Millennium Development Goals (MDG), on which prevention and treatment of diarrhea falls under the scope of Goal 7: “Ensure environmental sustainability” targeting clean water supply and sanitation accessibility (WHO, 2013). However, of all targets within the MDG, sanitation goals remain furthest from being fulfilled by 2015. Despite some progress, it was estimated around 2.6 billion still lacked access to improved sanitation facilities by 2011 (WHO, 2013).

2.2 Sanitation as an intervention

A major factor in the spread of diarrheal diseases is the lack of sanitation. According to the World Health Organization (WHO), sanitation is defined as “the provision of facilities and services for the safe disposal of human urine and feces”. Research has demonstrated that 88% of diarrheal deaths are caused by deficiencies in unsafe water supply, inadequate sanitation and poor hygiene practices (Lim ML, 2004; Liu et al.). Esrey et al. (1991), Tilley et al. (2008) and Fewtrell et al. (2005) claim that sanitation is one of the most effective and least expensive ways to prevent diarrhea and other life-threatening illness. The research performed by Esrey et al. (1991) shows how improvements in water availability with sanitation facilities achieve greater reductions in diarrheal infections than improvements in other interventions (such as water quality, education). However, around 40% of the world’s population does not have access to their own sanitary toilet.

WHO classifies sanitation facilities under two categories: unimproved and improved sanitation. Unimproved sanitation is defined as the management of human waste that "does not ensure hygienic separation of human excreta from human contact". Because unimproved sanitation facilities require little to no cost or infrastructure, it is practiced by the vast majority of people living in poverty in underdeveloped regions (See Figure 1). Unimproved sanitation facilities include: open defecation, pit latrines without a slab or platform, hanging latrines, bucket latrines, or any type of shared facilities (WHO/UNICEF, 2013).

Figure 1. Examples of unimproved sanitation: hanging latrine (left) and unkempt public toilet (right).

Source: S. Brownell, 2008

In contrast, an improved sanitation facility is referred to as the management of human waste that "hygienically separates excreta from human contact". Improved sanitation facilities include: flush/pour flush toilets (with piped sewer system, septic tank or pit), ventilated improved pit latrines, pit latrines with slabs, and composting toilets (Refer to Figure 2 for example) (WHO/UNICEF, 2013). Although satisfying the requirements to adequately manage sanitation, the existing types of facilities are not universally adopted by households due to technical complexity and significant costs necessary for installation and operation.

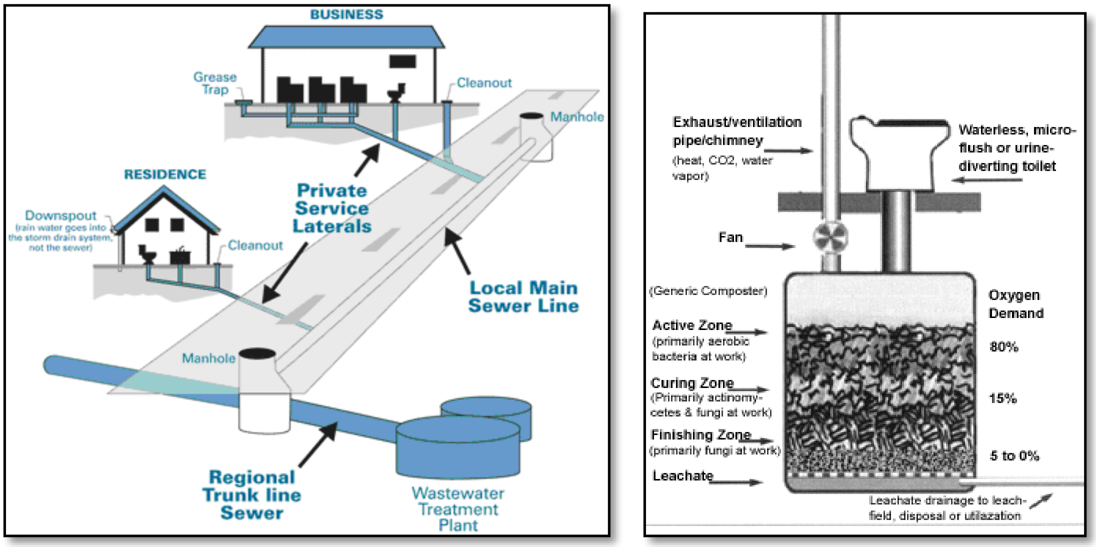

Figure 2. Diagrams of improved sanitation systems: pipeline sewer (left), and composting toilet (right).

Source: Left (http://brprojects.com/SSOProgram/SSOInfo.aspx?grpID=pub); Right (http://www.reuk.co.uk/Introduction-to-Compost-Toilets.htm)

2.3 Sanitation in the developing world

Diarrheal diseases caused by pathogens in fecal matter are widespread throughout low and middle-income countries. Proportionately, the regions of the world presenting the lowest sanitation coverage are sub-Saharan Africa, Southern Asia, Eastern Asia, and Latin America. Figure 3 illustrates that low sanitation coverage is predominant in these developing regions of the world (WHO/UN, 2011). Sanitation services and the management of waste are poorly supported even in most densely populated urban settings in low and middle-income countries. As a consequence, it is a common scenario in these regions to expect large volumes of waste, including human excreta, to be disposed into the streets or waterways causing blockages that aggravate flooding and the propagation of pathogens (Zurbrügg, 2002).

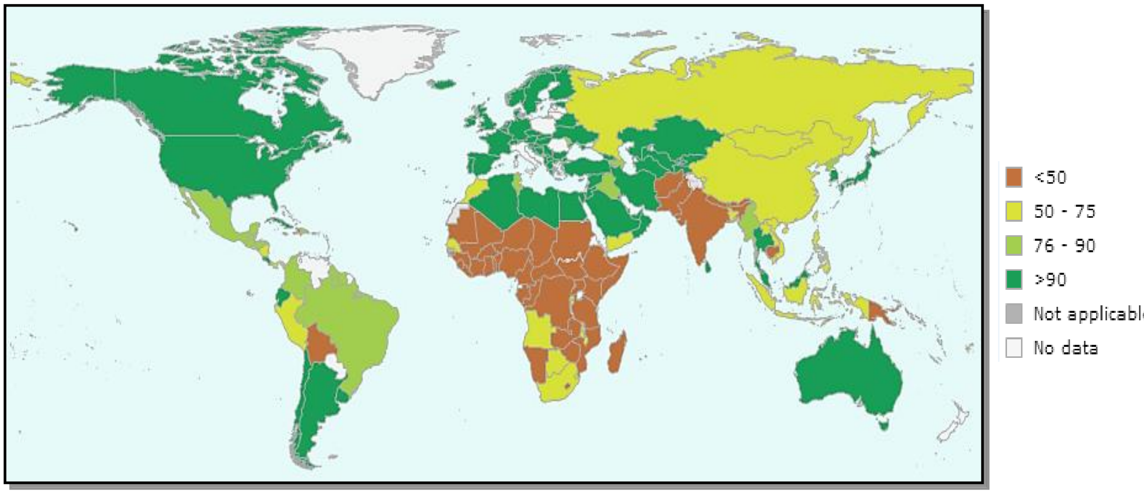

Figure 3. Proportion of population using improved sanitation facilities worldwide.

Source: World Health Organization, 2011

Aside from being visually unpleasant and a source of malodor, the consequences of a lack of improved sanitation in developing countries transcend the short term. For example, a 2003 study from United Nations Children's Fund (UNICEF) found that sanitation and hygiene related diseases were one of the leading causes of lateness to schools, absenteeism, poor performance and low academic achievements (Jasper, Le, & Bartram, 2012). The lack of sanitation facilities in a low and middle-income community means that members have to spend considerable amounts of time searching for a location, sometimes distant and unsafe, to defecate. A large burden is placed upon females who are forced to wait until it is dark to relieve themselves in open fields, where they are still under the risk of being attacked. In addition, young girls reaching the menstruating age tend to drop out of schools when proper sanitation facilities do not exist. As a result, this leads to an increase in female illiteracy and perpetuates gender inequality (Agberemi, 2006).

On that same note, the current state of unimproved sanitation has significant costs. These costs include both direct medical costs associated with sanitation-related illnesses and indirect losses through loss of productivity as well as reduced income from tourism and real estate (Commission on Macroeconomics and Health: Sachs, 2001). According to the WHO, providing improved sanitation and water supply for the world population of around 7 billion would cost around US$22.6 billion per year. However, achieving the MDG for sanitation only (75% of world population) would result in nearly $65 billion in savings every year through saved time, increased productivity, and avoided illness and death (Guy Hutton & Haller, 2004). WHO estimates that, on average, every dollar spent on improving sanitation returns about nine times the total initial investment (Commission on Macroeconomics and Health: Sachs, 2001).

These impacts are of concern as migration from rural to urban settings has maintained steady growth in the past 10 years. Figure 4 shows that increasing density in urban regions is present in almost all developing regions of the world. Given this trend, it is of particular interest to analyze the development of sanitation systems from a large-scale and urban perspective.

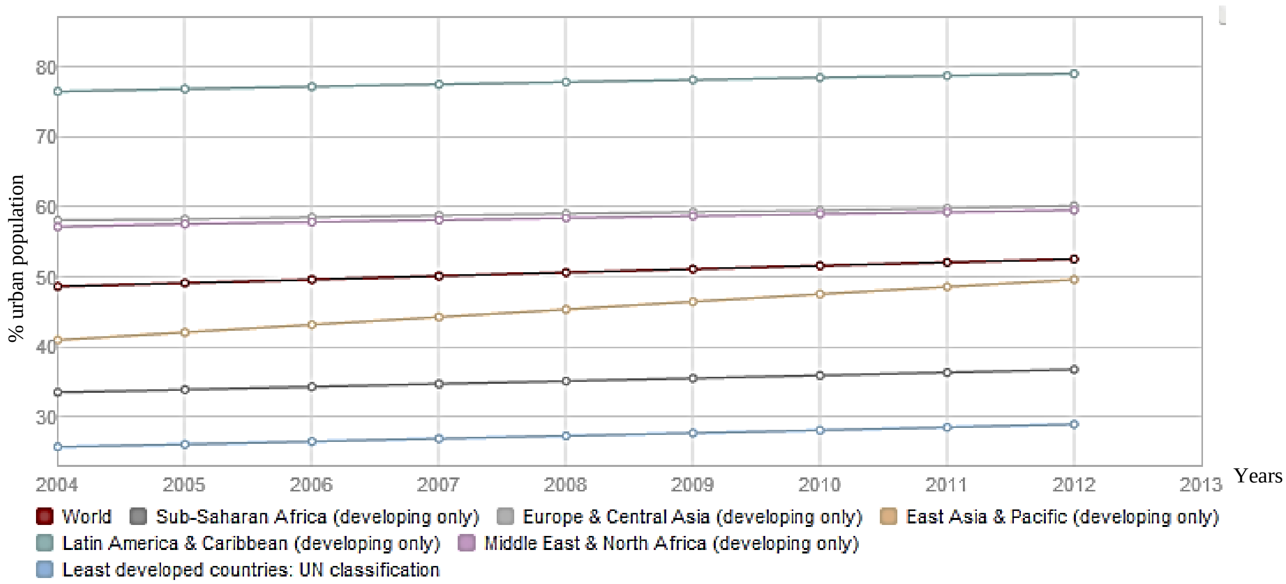

Figure 4. Increment of urban population in developing regions of the world.

Data and graph from The World Bank Group, 2012.

Much attention from international agencies has been focused to address the sanitation crisis affecting developing countries. Many programs receive funds to introduce sanitation facilities that serve entire communities. Paradoxically, some of these communities tend to achieve low rates of adoption and even lower rates of long term use (Balkema et al., 2002). In previous work (Cruz Diloné, 2013), a systematic review of the literature was performed for the critical assessment and evaluation of an extensive pool of data concerning this topic. During this research it was observed that the slow expansion of sanitation coverage is not only due to lack of attention to sanitation needs or poor management from institutions, but rather to unaddressed social, economic, technical and environmental barriers. For example, numerous aid programs have attempted to deal with improving sanitation in the developing world, but they have lacked community and governmental support, comprehensive and accurate data collection and consistent funding, have been too small scale and short-term, are inadequately suited or detrimental to local environmental conditions, and have not addressed the real roots of problems or followed up through monitoring and accompaniment. Therefore, there is a pressing need to develop sustainable sanitation systems that can be widely adopted and sustain usage over time, especially in those regions of the world with lower sanitation coverage and high mortality rates due to diarrheal diseases. To that end, it is necessary to analyze the sustainability of sanitation in its many dimensions to effectively engage in promoting well-being in the developing world for present and future generations.

For this research, a sustainable sanitation system is defined as one that fulfills the functional and technical requirements of sanitation while causing minimal or no disruption, or causing improvements to the environment, economy, society (including the health of a community) and governance.

2.4 Structure of the document

Section 3 of this document defines the problem statement and the main objectives of the research. A summary of the literature review can be found in Section 4 presenting published work on approaches to (i) assessing environmental impacts of sanitation systems, including their insights and limitations, and (ii) ranking and rating alternatives when multiple criteria are involved. The research methodology is presented in Section 5 along with the scope of work. Results and its respective discussion are disclosed towards the end of Section 5. Lastly, a summary of the conclusions and recommendations is shown in Section 6 along with prospective future research in Section 7.

3. Problem Statement

The lack of infrastructure in developing countries is both an impediment for the sustainability of waste management systems and an opportunity to innovate. In terms of providing improved sanitation, systems can range from simple (such as a simple pit latrine with a slab) to highly technical (such as a self-powered tertiary wastewater treatment facility with sludge and methane recovery serving a large community). However, efforts to develop different types of infrastructure at different levels of complexity have not significantly improved sanitation coverage, mainly due to unaddressed and contextual social, economic, technical and environmental needs. Low and middle-income countries have been the recipient of development aid from a number of organizations. With few exceptions, much of this aid has not resulted in sustained sanitation usage over time (Del Valle Cavagnero, Godinho, & Abrantes, 2013; McConville, 2006; Peter Wampler, 2011). It is therefore paramount that the selection of a particular sanitation system provides an effective provision and improvement of sanitation services for an increasing urban population. Yet, the necessary data to perform such decisions is not fully available. Given the aggravated environmental and economic conditions and the lack of infrastructure in these countries, the selection of a sanitation system becomes challenging for NGO's, government agencies and other groups of interest. Quantifying the costs and benefits to the environment of various sanitation options is one step in helping decision makers make better choices. Because these systems are of such large scale, their positive and negative impacts are also of significant proportion, highlighting the importance of optimizing these decisions. Bearing this in mind, the following statement is used to summarize the problem:

> *The environmental sustainability of large-scale urban sanitation systems in the majority of developing countries is complex and not entirely explored; therefore, there is a need for approaches to adequately evaluate and compare the environmental performance of sanitation systems and thus better inform decision makers in developing sustainable sanitation systems.*

4. Literature Review

4.1 Sanitation and Sustainability

As pointed out by various authors (Guy Hutton & Haller, 2004; G. Hutton et al., 2007; Montgomery, Bartram, & Elimelech, 2009) and global institutions like World Bank (Feachem, Bradley, Garelick, & Mara, 1983; Solo, 1998) and World Health Organization (Commission on Macroeconomics and Health: Sachs, 2001), improvement of water and sanitation is fundamental for the development of healthy communities, and results in significant economic and social gains. Achieving these improvements in a sustainable manner will optimize and extend these benefits significantly. A key step towards achieving sustainable sanitation is the comprehensive assessment of the needs of a system, considering technical as well as environmental and socioeconomic criteria. According to the Sustainable Sanitation Alliance (SuSanA), a sustainable sanitation system has to be "economically viable, socially acceptable, technically and institutionally appropriate, and protect the environment and natural resources" (Joensson, Richert Stintzing, Vinneras, & Salomon, 2004).

The impacts on the environment from deficient or poor sanitation systems are numerous. In places where defecating in the open or in plastic bags, also known as *flying toilets*, are common practices, pathogens can easily spread to plants and animals, contaminating food and drinking water supply (Zurbrügg, 2002). Moreover, plastic bags used in flying toilets are generally not biodegradable and thus contribute to solid waste pollution (Mwakugu, 2007). In more urbanized regions, a common manifestation of poor sanitation management is the discharge of sewage into the environment (e.g. streams, rivers, lakes, wetlands, and the ocean) (Pujari et al., 2007). This practice results in the loss of valuable biodiversity. For instance, the presence of human excreta in water can increase nitrogen levels (Muñoz, Canals, & Clift, 2008), and consequently, cause eutrophication. Water eutrophication causes overgrowths of algae, which in turn, can deprive other species from oxygen and sunlight.

4.2 Environmental assessments of sanitation

Material Flow Analysis (MFA) and Box Flow Analysis (BFA) have been used to evaluate the risks for environmental pollution from sanitation systems and to quantify their resource recovery potential. The method of MFA quantifies flows of materials in a defined system in order to understand its effects on the natural and industrial ecology. A study from Ushijima et al. (2013) determined the economic and environmental feasibility of ecological sanitation systems in an urban slum scenario through an analysis of materials and value flow analysis by comparing their direct and externalized implications. Meinzinger et al. (2009) analyzed nitrogen and phosphorus flows of septic tanks, pit latrines and urine diversion toilets from a small rural town in South Ethiopia showing the potential to obtain significant amounts of plant nutrients (with potential value as fertilizer) from sanitation systems. However, these methods focus on the use phase of sanitation systems and its byproducts while leaving out the implications of other phases of their life-cycle. In addition, methods for MFA and BFA do not enable an appropriate comparison between alternatives of a system with the same function.

Life-cycle thinking has been recurrently used as a method to measure the sustainability of water and sanitation projects (Renou, Thomas, Aoustin, & Pons, 2008). Life-Cycle Assessment (LCA) is useful to evaluate the impacts of products and services during all phases of their life-cycle. This in turn can be helpful to appropriately compare alternatives, identify opportunities for improvement on design or plan for mitigation in a systematic manner. The methodology, standards and terminology behind LCA are defined by ISO 14040 (2010), and exemplified in many case studies among industrial ecologists, organizations, and academia. Although research and case studies have been conducted independently, a common framework for LCA can be described by following four phases: Goal and scope definition, Inventory analysis, Impact assessment, and recommendations assessment through Interpretation.

LCA studies on small and large wastewater treatment plants have been successful at identifying diverse environmental impacts such as water eutrophication and terrestrial ecotoxicity (Gallego, Hospido, Moreira, & Feijoo, 2008), the trade-offs between environmental impact indicators and operational costs (Rodriguez-Garcia et al., 2011), and the burden of energy and global warming potential of different wastewater treatment systems (Houillon & Jolliet, 2005). The LCA performed by Thibodeau et al. (2014) was able to show that source-separation systems (where solid and liquid excreta are separated in the point of generation) yield higher negative impact scores for human health, ecosystem quality, climate change and resource depletion compared to conventional centralized wastewater treatment system, mainly due to significant metal emissions to the soil. Benetto et al. (2009) conducted a comparative Life-Cycle Assessment between a centralized ecological sanitation system and a conventional centralized wastewater treatment system, thoroughly analyzing the potential allocation of byproducts of each system and measuring their environmental performance on a small-scaled urban scenario in Luxemburg. This study concluded that the largest environmental impact caused from ecological sanitation comes from transportation of waste, thus making it more suitable for small-scale waste management schemes. The study also places attention on the fact that conventional centralized wastewater treatment systems have very poor environmental performances in terms of terrestrial ecotoxicity and energy requirements, and thus, other alternatives should be investigated. In addition, not all systems for ecological sanitation have been evaluated nor compared to other sanitation alternatives on a large scale.

One significant limitation to performing LCA is that it is data-intensive analysis, and therefore requires a relatively large amount of time and resources spent on gathering, organizing and interpreting information. A number of software tools and databases are available to model environmental LCA of products and systems on a variety of large scale industries such as textile, transportation, waste management, agriculture, and various manufacturing outputs which eases the process of gathering and organizing data. However, these software, databases and units of measurement for environmental impact are developed and oriented based on standards of well-developed industrialized countries which brings certain degrees of uncertainty when attempting to model LCAs in scenarios with holistically different conditions. This is a significant barrier to produce accurate and reliable environmental LCA models, which as discussed earlier in this document, are direly needed by decision makers to identify and select alternatives of sustainable sanitation systems.

4.3 Approaching decision making

The environmental impacts quantifiable through the LCA can vary in magnitude, importance, and unit of measurement. Understanding and analyzing these results is part of the interpretation phase of an LCA and enables decision makers to have a better understanding of the environmental burden associated with the life-cycle of a system or many alternatives. The interpretation of these results is highly contextual and requires a holistic understanding of the environmental and stakeholder's needs and goals of the assessment. Available impact assessment tools that aid in the interpretation, such as ReCiPe, are commonly used by LCA practitioners worldwide, yet originated by entities in developed regions of the world like the European Union (EU) and the US. Although these available tools can be potentially modified to account for global statistics these can result in the addition of uncertainties and blur the significance of results.

Multiple-Criteria Decision Analysis (MCDA) can be useful to tackle the uncertainties and challenges present in decision-making, such as comparing and ranking criteria and alternatives (Belton & Stewart, 2002). MCDA methods require the decision maker to structure the decision analysis by defining goals, criteria, alternatives and constraints, and to evaluate this structure through mathematical models. In the process of evaluating the alternatives to a decision, it often becomes apparent that the outcomes of one or more course of actions are uncertain and that there are difficulties in comparing criteria with different magnitude (i.e.: qualitative vs quantitative). Analytic Hierarchy Process (AHP) is a well-known MCDA approach for structuring complex scenarios, deriving scale priorities, and helping decision makers to choose the best alternative among a discrete set of alternative scenarios (Triantaphyllou, 2000). In AHP, the decisions are structured in a manner that the comparisons are done between elements of the same category, also described as pairwise comparisons. AHP is also useful to extract priorities and weights from quantitative and qualitative sources in a relative manner, and in doing so, avoid the difficulties of justifying weights that are arbitrarily assigned by decision makers (Forman & Selly, 2002). In this process, the decision maker carries out pairwise comparisons which are then used to develop overall priorities for ranking the alternatives. Another feature of AHP is that it allows one to measure and provides a means to improve consistency in the process of defining priorities. Inconsistencies are often found to be a result of clerical errors, lack of information, inadequacy in the structure of the model, or general real-world incongruities (Forman & Selly, 2002).

Many applications of AHP can be found in the literature in a wide set of areas: personal choices, social and policy, engineering, education, government, sports, management, etc. Published literature describing AHP applications to environmental analyses is still growing. Some of these published applications involve energy planning (Hamalainen & Seppalainen, 1986; Li & Chang, 2011), consumer preferences for environmental policy (Uusitalo, 1990), and the evaluation of environmental impacts of manufacturing processes (Ong, Koh, & Nee, 2001). In these works, AHP is able to address MCDA while considering judgment from single or multiple decision-makers. Seppala et al. (2008) analyzed different decision analysis frameworks for LCA. Among the methods described, AHP was cited as one of the appropriate tools for supplementing decision analysis to LCA. For instance, an application of AHP and qualitative LCA approaches was put forth by Pineda-Henson et al. (2002) focusing on manufacturing processes. AHP was shown to be an effective support tool for LCA as the environmental concern factors evaluated were hierarchically structured and compared. For these reasons, AHP can be used as a tool to support the interpretation phase of the LCA and thus to determine an objective ranking of the importance of different types of environmental impacts in comparative LCAs, such as the one proposed in this document.

Previous attempts to couple LCA methodologies with AHP have mostly been analyzed in a qualitative manner or on the assessment of products, not systems. Similarly, recommendations from previous studies in environmental life-cycle assessment of sanitation systems in developing world scenarios were drawn from inaccurately modeled systems and thus draw conclusions with considerable uncertainties. Utilizing the decision analysis features of AHP to complement some of the limitations of LCA can potentially enhance the significance and reliability of environmental assessments.

5. Research Methodology

5.1 Overview

The methodology employed in this research utilizes steps from both environmental Life-Cycle Assessment and Analytic Hierarchy Process. This method was chosen to allow quantifying and comparing a variety of environmental impacts associated with all life-cycle stages of selected sanitation systems and consequently provides a ranking that best fits the context of analysis. Relative ranking of the systems is verified by AHP using through defined priorities from decision makers. This approach allows practitioners to obtain comparable quantitative results for competing systems and to systematically approach decision making in complex and dynamic scenarios.

The method was applied to a model based on a case study to demonstrate its applicability and limitations. The model considered potential sanitation systems operating under a range of scenarios in an effort to capture the potential environmental impacts associated with sanitation systems, and to support the decision on future course of action. The three alternatives defined have the same system boundaries; they transport and treat household human excreta. The physical boundaries of the scenarios were defined after examining maps, reviewing the literature, and remotely contacting local experts on the subject. A sensitivity analysis was then performed to reveal the relationships between input and output variables in the model and to help identify the key limitations of both the analysis and the methodology, which can be investigated in future research.

While the quantitative analyses conducted in this study provide results that are more adaptable to variables, the complementary qualitative analysis will allow for the interpretation of these results in a more detailed and contextually precise manner. Therefore, this framework seeks to harness both quantitative and qualitative analysis in a structured and consistent style. A summary of the steps involved in this method is shown in Figure 5.

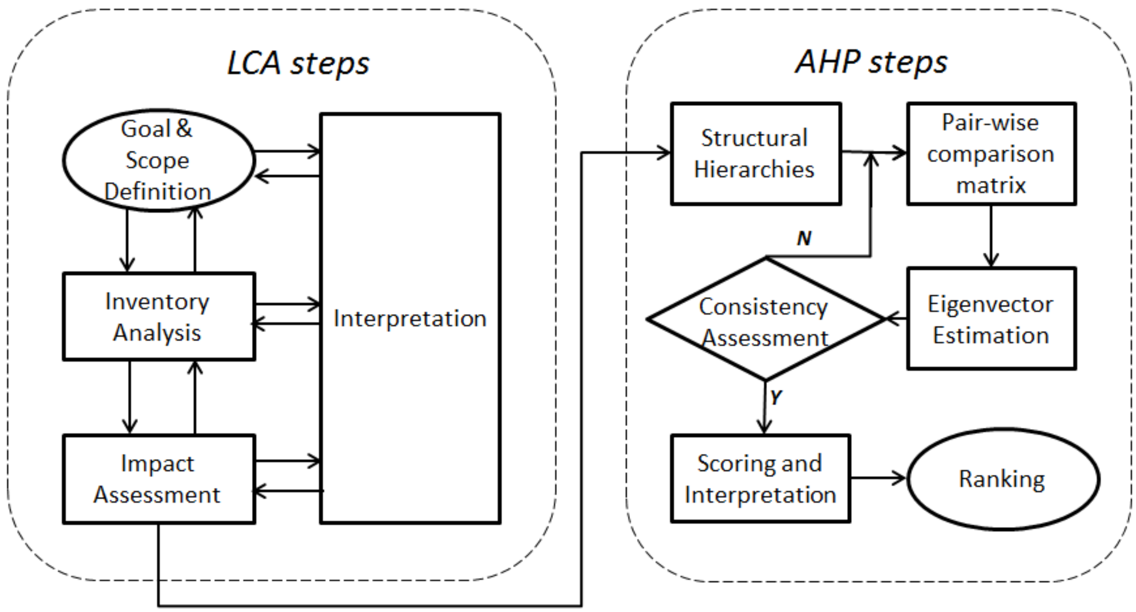

Figure 5. Process flow diagram of the steps involved in the framework developed.

It is important to point out that the framework used in this environmental Life-Cycle Assessment is similar yet not the same as the standards published by the International Organization for Standardization (ISO) (2010). For instance, peer-reviewed evaluations were not possible due to limited time frame, the project scope and the intended audience of this research. Another marked difference is that the impact assessment step is further analyzed using methodologies of Analytic Hierarchy Process. ISO 14042 shows a rather restrictive stance on weighting in LCA claiming "weighing shall not be used for comparative assertions disclosed to the public". However, AHP does not prescribe right and wrong answers but helps select the course of action that best reflects the decision maker's goals and understanding of the context. The intent of this research is not to deliver a statement but to partially close a research gap as discussed in Section 3 of this document. Due to these marked differences and conflicts, this study is not claiming to be an LCA as defined by ISO but employs the majority of is holistic steps.

In summary, the methodological framework proposed in this research is relatively new and has not been previously used to approach evaluation and decision making in a developing-world context. This research intends to partially close gaps from a methodological perspective, and to provide a more systematic understanding of the environmental implications of selected sanitation systems in a developing-world context.

5.2 Life-Cycle Assessment

5.2.1 Goal and scope definition

Defining goal and scope of an LCA consists of the description of the system including the purpose of the study, the system boundaries, and a functional unit. Defining the goal of the study helps to determine potential sources of the data required for the study, the future use of the results and the audience to which the study is addressed. The system boundaries are set in order to provide some context on the scope and depth of the many processes that need to be investigated in the study. A functional unit is a quantification of the service delivered by a product or system, usually measured as the functional output in terms of magnitude and/or duration, which enables its comparison with alternative systems (Cooper, 2003).

5.2.1.1 The case study of Cap-Haïtien, Haiti

Haiti is the poorest country in the western hemisphere with 80% of the population living under the poverty line ($1.25/day in 2009 according to The World Bank); while 54% subsist under extreme poverty (CIA, 2013). The fact that forests cover less than 2% of the territory and that the majority of the soil is deteriorated to a state of low agricultural productivity are evidence of the severe environmental degradation affecting the country. The effects of these critical environmental conditions are reflected in Haiti's socioeconomic profile, as agriculture is the second largest economic activity of the country employing a significant percentage of the labor force (Smucker, White, & Bannister, 2002).

Among the alarming conditions burdening Haiti, access to improved sanitation facilities is one of the most striking. Access to basic sanitation in Haiti declined to only 36% after 2010, when the average for Latin America and the Caribbean is at 80% coverage (WHO/UN, 2011). Until the existence of Direction Nationale de l’ Eau Potable et de l’Assainissement (DINEPA) in 2009, there were no government institution overseeing supply of sanitation services for the overall population (DINEPA, 2012) while sanitation coverage gradually declined from 45% in 1990 to 36% in 2011 (WHO/UN, 2011). DINEPA’s work, as well as most of the development aid, has focused in the cities of Port-au-Prince and Cap-Haïtien where the largest urban populations of the country are situated (WHO/UN, 2011). In September 2011, DINEPA finalized the construction of three waste stabilization ponds (2 in Port-au-Prince and 1 in Cap-Haïtien); however, operative complications emerged within the first year leaving only one facility in Port-au-Prince still in operation (Kramer, Preneta, & Kilbride, 2013). In addition, the remaining stabilization ponds can only serve a fraction of Port-au-Prince wastewater needs. This lack of sanitation services is an ongoing contributor to the propagation of the cholera epidemic, a lethal diarrheal disease, with over 8,000 reported deaths as of 2013 (*National Plan for the Elimination of Cholera in Haiti*, 2012). Various analyses by Wampler et al. (2011; 2011) and Tassel et al. (2009) over the geological and ecological conditions of Haiti concluded that current conditions enable the existence of shallow aquifers that are prone to be contaminated by water-borne pathogens, and thus, recommends that funds should be spent on improving water and sanitation resources rather than vaccines. At the same time, much of the aid supplied by various international organizations is still directed to address the cholera epidemic in the form of vaccines and education, and have not focused on longer term development of sanitation infrastructure and programs (Gelting, Bliss, Patrick, Lockhart, & Handzel, 2013).

Cap-Haïtien, as the second largest city in Haiti with a population of 155,500 by 2009 (IHSS, 2009), serves as an example of an increasingly growing urban area in a developing country with exposure to different sanitation systems but poor sanitation coverage overall. Aside from stabilization ponds, other sanitation alternatives seen in Cap-Haïtien include open defecation, flying toilets, hanging toilets, composting toilets, small sewer grids with discharge to waterways, septic tanks, and latrines. The analysis of Remy Kaupp along with Oxfam (2006) presented a review of the sanitation options in Cap-Haïtien in 2006. Results included that public sanitation systems were poorly managed and likely to be abandoned in the long term due to lack of appropriate maintenance while private options were expensive to build and maintain and performed poorly in the limited space of the urban and peri-urban regions of the city. In the end, the study recommends future research on a low cost ecological sanitation option and supply-driven business model.

Sustainable Organic Integrated Livelihood (SOIL), a non-profit organization based in Haiti, has a trajectory of studies and programs on ecological sanitation and sustains a network of urine diversion toilets serving the community of Shada and various urban slums in Cap-Haïtien. The human waste collected from this network is transported to a composting site in the surroundings of Cap-Haïtien where fertilizer is produced for local use in agriculture and reforestation. Kramer et al. (2012) presented an analysis of the technical and economic performance of a thermophilic composting facility based in this operation in Cap-Haïtien. Similarly, the NGO PROTOS completed a program in the period of 2011-2013 to improve water and sanitation management in a working-class district in Cap-Haïtien (PROTOS, 2013). The results reported include the installation of latrines in 12 different schools and the involvement of local stakeholders to promote development through improved water and sanitation management. Alternatively, Meegoda et al. (2012) have recently presented the feasibility of a functional sanitation system that outputs biogas and fertilizer without using external energy. While projects on sanitation systems are emerging in Haiti, no study comprehensively analyzing the environmental impacts of these systems was found. This situation provides a prospective scenario for demonstration of the method proposed and will serve as a case study.

5.2.1.2 System Boundaries

The simplified process flow diagram presented in Figure 6 illustrates the scope considered for each system of interest. The result is the definition of three scenarios for sanitation systems in Cap-Haïtien, Haiti: the Compost Facility scenario, the Sanitary Sewer System scenario, and the Waste Stabilization Ponds scenario. These alternatives were identified among systems that are currently in service on a larger scale compared to others, as described in the review of the case study. Impact allocation methods and the statement of assumptions for specific scenarios are further detailed in the section Life-Cycle Inventory Assessment.

The use of water and other inputs, such as energy and transportation, are accounted accordingly. The use of toilet paper and soaps, or substitutes, is neglected because it is assumed that users will use the same amount, type and rate regardless of the scenario.

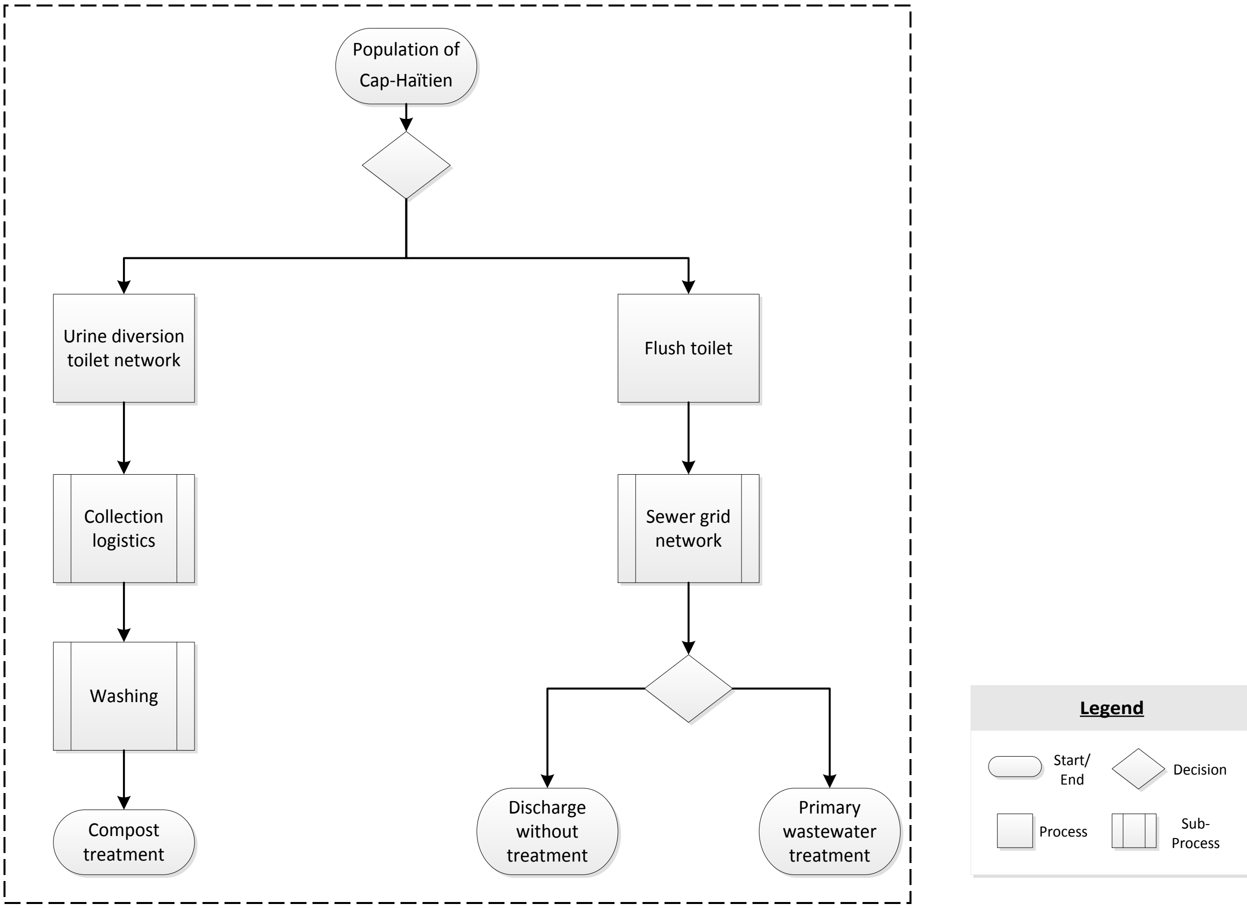

Figure 6. Simplified process flow diagram of the scenarios considered for the study.

5.2.1.3 Functional Unit

The functional unit determined for this case study is: *the provision of sanitation services for of 22,214 households each outputting 2.45kg of feces per day in an urban setting for 15 years*.

This unit was defined based on a series of assumptions. For the number of households, an average of 7 people per household was assumed based on field surveys on Borgne and Milot conducted during 2013[1] and 2014 (O'Connor, 2014) and last available demographic statistics from the Haitian Institute of Statistics and Data Processing (Institut Haïtien de Statistique et d'Informatique) (2009). Time frame was defined based on the review of technical performance of sanitation infrastructure by Machado et al. (2007) coupled with estimations of life expectancy of sewer systems by a report from the United States Environmental Protection Agency (EPA) (2002). Unlike the infrastructure used in the compost scenario modeled in this study, data on lifespan of sanitation sewer infrastructure is readily available. Although the life expectancy of a sewer system is estimated to be an average of 50 years, the same analysis shows that life expectancy of treatment equipment varies from 15 to 20 years depending on maintenance. In addition, the amount of feces produced by a person largely depends on the composition of their diet. According to Feachem et al. (1983) fecal excretion rate per person can vary from 250 grams to 350 grams on a daily average for a common low-protein, high-grain diet common in developing countries. In summary, this functional unit was chosen to measure the effects on a large scale and to be able to appreciate the marginal impacts of all alternatives in a worst case scenario.

5.2.1 Life-Cycle Inventory Assessment

The life-cycle inventory (LCI) assessment consists of the collection of data regarding all materials and process units concerning the systems being examined. The purpose of the LCI is to quantify the inputs to the systems under analysis based on their associated mass flows, energy usage, as well as emissions into water, soil, and air. In addition, general and process specific assumptions can be stated in the LCI. Commercial LCI databases include datasets based on data collected by practitioners during their work with companies, and public and academic institutions. These databases can contain information of materials and processes

[1] The author spent a total of 12 days in Cap-Haïtien, Haiti during the month of June of 2013. Although the visit did not cover all regions of the city explored in this thesis, it has been essential for defining the scenarios in the sense of understanding the general prevailing conditions, as well as country/culture related aspects.

from a variety of industries, including: agriculture, construction, transportation, textiles, electronics, plastic and metals processing, energy, etc.

The Ecoinvent v2.2 database was used in order to model materials, processes and life-cycle scenarios in Simapro 7. Simapro is a high-end LCA software tool that utilizes predetermined datasets to simulate materials and processes of products and systems in order to model life-cycle assessments. The Ecoinvent 2.2 datasets are based on industrial data and have been compiled and reviewed by European research institutes and LCA consultants as occurred in 2010.

Materials and processes that are not readily available in the datasets were modelled using a list of materials and processes available in Simapro and referencing external data as appropriate. These inputs are assumed to be representative of reality, as intricate evaluations and validations are outside the scope of this analysis. The transportation operations and distances for these materials, from their points of processing to the intended site of use, have been estimated and included in the analysis. The operational efficiency during the use phase of each of the scenarios was assumed to be constant although the author is aware of the effects of chemical reactions, weather conditions and other variables affecting each of the sanitation systems. Impact allocation of by-products is examined individually further into this document. In SimaPro, the end-of-life (EOL) scenario of a product or a system is defined by developing a waste scenario according to the processes and disposal operations associated with landfilling, incineration, and recycling of materials (Goedkoop et al., 2010). However, none of these scenarios is currently available in Cap-Haïtien, Haiti. Current practices include uncontrolled dumping in many sites of the city and open incineration is usually practiced by locals to reduce volume of solid waste (IADB, 2014). For the sake of this analysis, a dumpsite facility will be modelled assuming there is infrastructure already available in the outskirts of the city approximately 6 miles from the center of the city (See Figure 7). It is reasonable to assume this since there is a lack of local infrastructure and local market to recover these materials for recycling. The estimation for the siting of the dumpsite was assumed using guidelines from the United States Environmental Protection Agency as possible (1993).

The transportation of raw materials and finished goods are analyzed and represented in the Transportation phase. Transportation distances were estimated using a variety of online tools. Shipment and transportation distances by road were estimated using applications of Google Maps while oceanic freight distances were estimated using an online international routing tool http://www.searates.com/reference/portdistance/ (See Figure 8). Likewise, railroad shipment distances were estimated using online calculator with the US rail map http://www.spoornet.co.za:70/CalculateDistance.asp. Figure 9 shows a screenshot of the reference used to estimate road distances utilizing the GPS-derived positions Google Maps and Google Earth. The accuracy of remotely estimating these distances depends upon source data. For the purpose of this research, inherent inaccuracies of this tool will be accepted.

Figure 7. Assumed location of municipal solid waste dumping facility

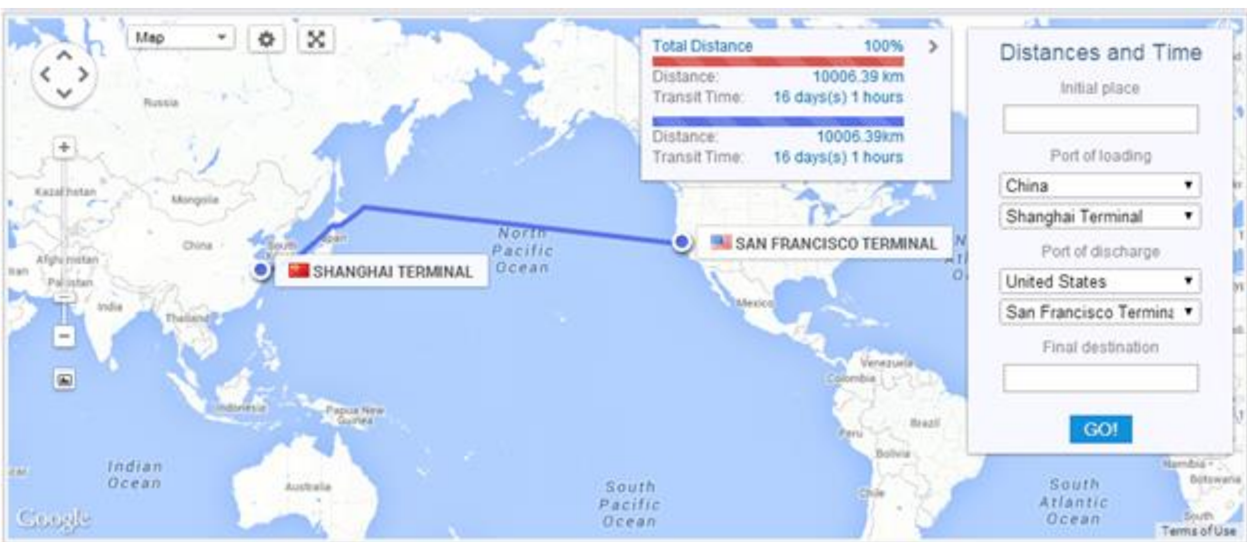

Figure 8. Estimation of the transportation distance for oceanic freight between Shanghai, China and California, USA.

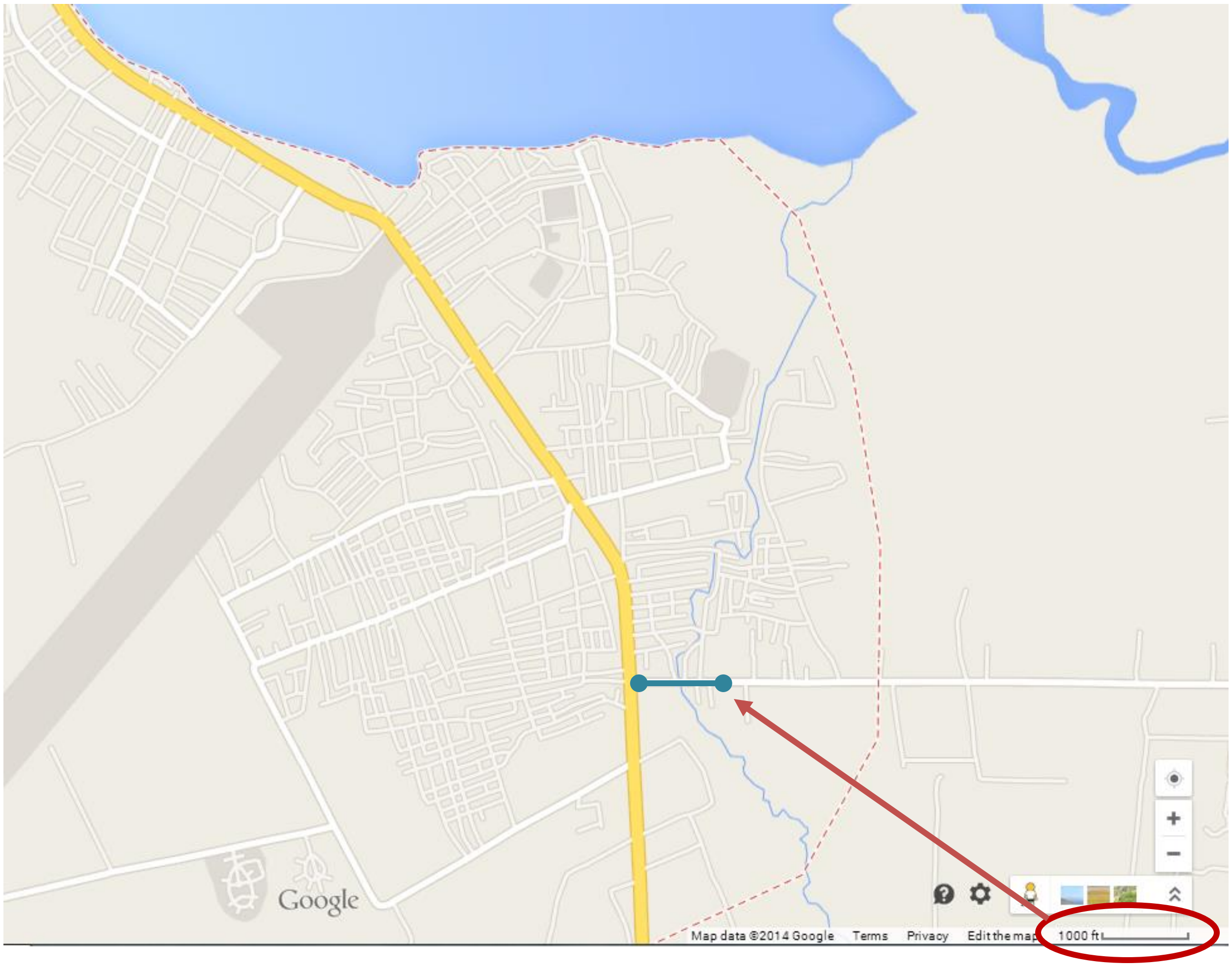

Figure 9. Example of the reference for estimation of distances in Google Maps.

The following subsections describe the specific assumptions and calculations concerning the alternative systems under study.

5.2.1.1 Urine diversion toilet with collection network to off-site composting facility

An urine-diversion toilet (UDT) network is a sanitation system where urine and feces from human defecation are separated at the source and collected for further composting into usable fertilizer (See Figure 10). To model this scenario, data from the UDT network run by SOIL in Cap-Haïtien will be used. In this sanitation system, human waste is separated at the source using a plastic fixture attached to a toilet seat; urine is disposed by the user while feces are collected in a bucket and transported to an off-site composting facility for treatment (Kramer et al., 2013). An in-depth description of materials and sub-processes involved in this system is described in the following subsections.

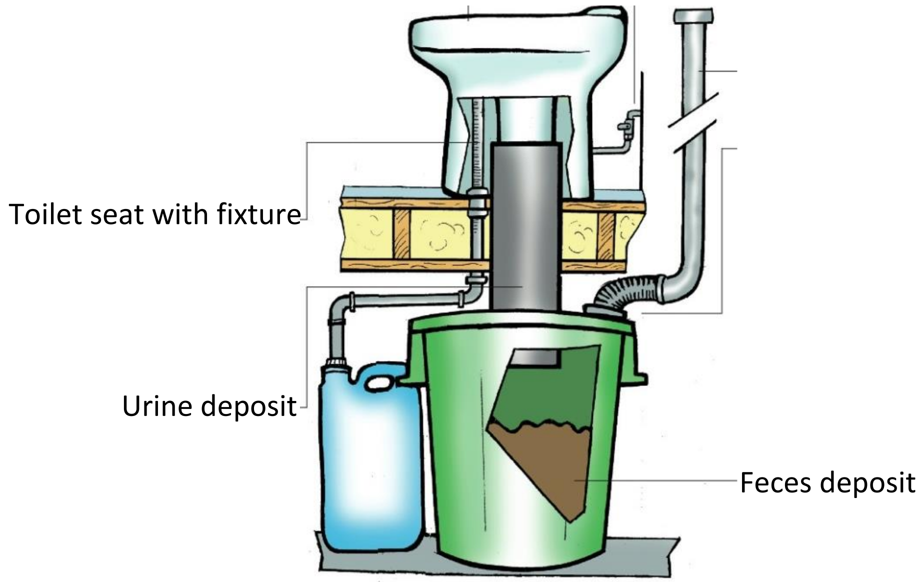

Figure 10. Schematic of a generic ventilated urine diversion toilet.

Source: http://www.ecovita.net/EcoDry

5.2.1.1.1 Materials and processes

The materials considered for this system consists of: urine-diversion toilets (a conventional polypropylene (PP) toilet seat with a lid, a thermoformed high-density polyethylene terephthalate (HDPE) fixture, a 5-gallon PP bucket for the feces, and a gallon polymer container for the urine), 55-gallon HDPE drums for collecting household solid waste, a diesel truck for transportation, water and detergent for washing the drums after disposing the wastes into the facility, and the building materials (concrete slab, softwood lumber, fastener, roofing sheets, shipping pallets, and discarded sugar cane fibers) composing the composting facility (Refer to Figure 11). Land occupation is also accounted for accordingly, and it is assumed that the land used is fallow and inactive for other purposes.

Figure 11. SOIL's compost facility in Limonade, Cap-Haïtien.

Source: Theo Hiutema, 2014

The majority of these materials and products are not readily available in the datasets in SimaPro. In order to accurately model these elements in SimaPro, the materials were quantified in terms of mass and weight unit as possible, as some are provided in volumetric units. In order to convert volumetric units into weight units, common density values were averaged then multiplied by the volumes estimated per material. The volumes of these materials were determined by analogy-based references from commercial equivalents. In example, SimaPro provides wood based materials in a volumetric unit. The individual weight of the softwood lumber used in the building structures was identified by computing the specific gravity of spruce (0.431), a common softwood lumber for this application, and the volumetric unit of $1m^3$ as provided by SimaPro. This provides a weight based material for softwood lumber with an estimated weight of 431kg per m3.

Shipping pallets and the sugar cane fibers used to fill them are considered salvaged byproducts of other processes because otherwise these materials would likely be discarded with no further purpose. The impacts associated with the extraction, processing and prior uses of both the shipping pallets and the sugar cane fibers are not accounted for in the model since these materials were not intended for the purpose of this system. The model does include the transportation of these materials from their point of last use to the compost facility and the end of life processes associated with their disposal. It is assumed that shipping pallets are sourced from the port of Cap-Haïtien while sugar cane bagasse is sourced from a local processing plant.

5.2.1.1.2 Transportation

The transportation phase can be categorized from two sources: gathering/disposing materials for infrastructure and operation logistics. In general, plastics used in hardware and most of the building materials are assumed to be imported from China, United States and Dominican Republic using oceanic, railroad and road freights as applicable. Operational logistics are conveyed through road transport using a small diesel truck (See Figure 12). A staff team visits each household collecting the solid waste from the buckets which are later moved into a 55-gallon drum. The collected solid wastes are then transported to an off-site composting facility every 7 days (Kramer et al., 2013). SOIL's compost facility is currently located in the community of Limonade, in the outskirts of the city of Cap-Haïtien (Refer to Figure 13). The same location will be assumed for this model as there are unknown factors and uncertainties associated with the feasibility and capabilities of other locations to run such operations.

Figure 12. Frontal and side view of the diesel truck used by SOIL, also known as "Poopmobile". Source: Theo Hiutema, 2014

Overall transportation distances and number of households are estimated using the remote visual features of Google Maps. Figure 14 shows a visual representation of the estimation of households that were tallied by region. This method was also useful to estimate routing and amount of trucks necessary to service specific regions of the city considering population density. The level of efficiency of the routing, fleet size, and the overall transportation operations is directly correlated to the environmental impact of the transportation phase, and overall life-cycle of a system. Although the author has made the best effort to efficiently configure this model, the optimization of these variables is outside of the scope of work.

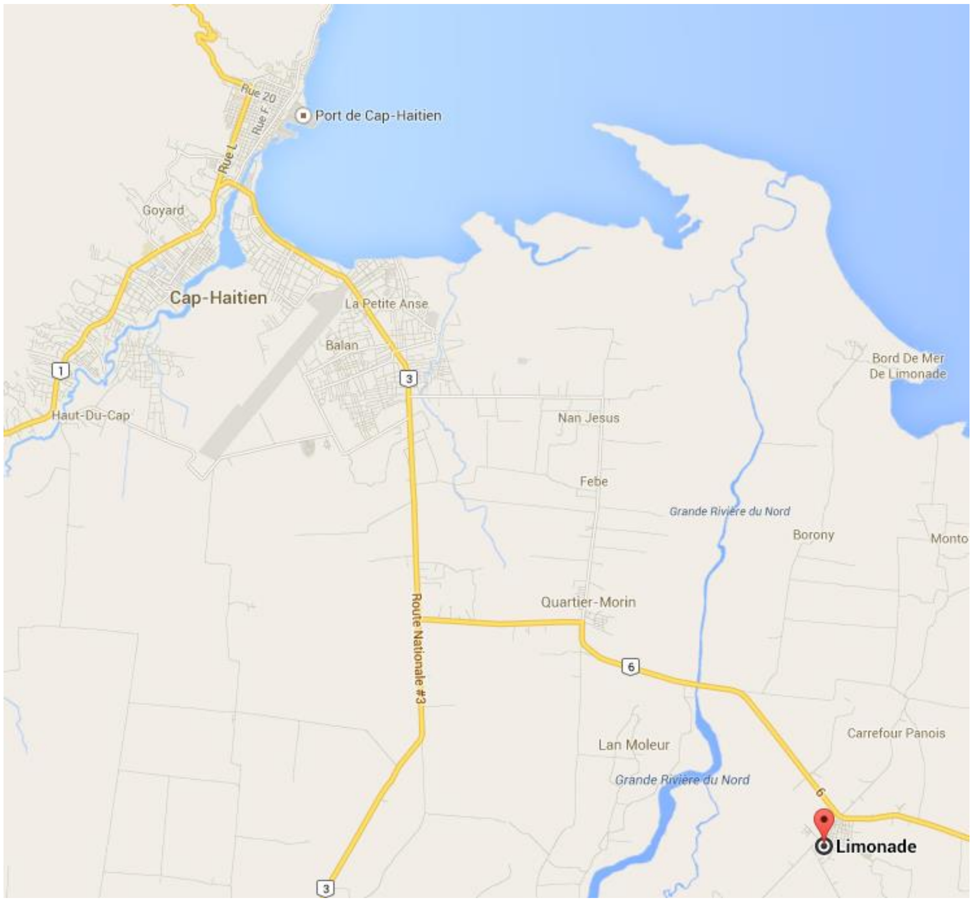

Figure 13. Map view with the location of the community of Limonade in relation to the city of Cap- Haïtien.

Source: Google Maps

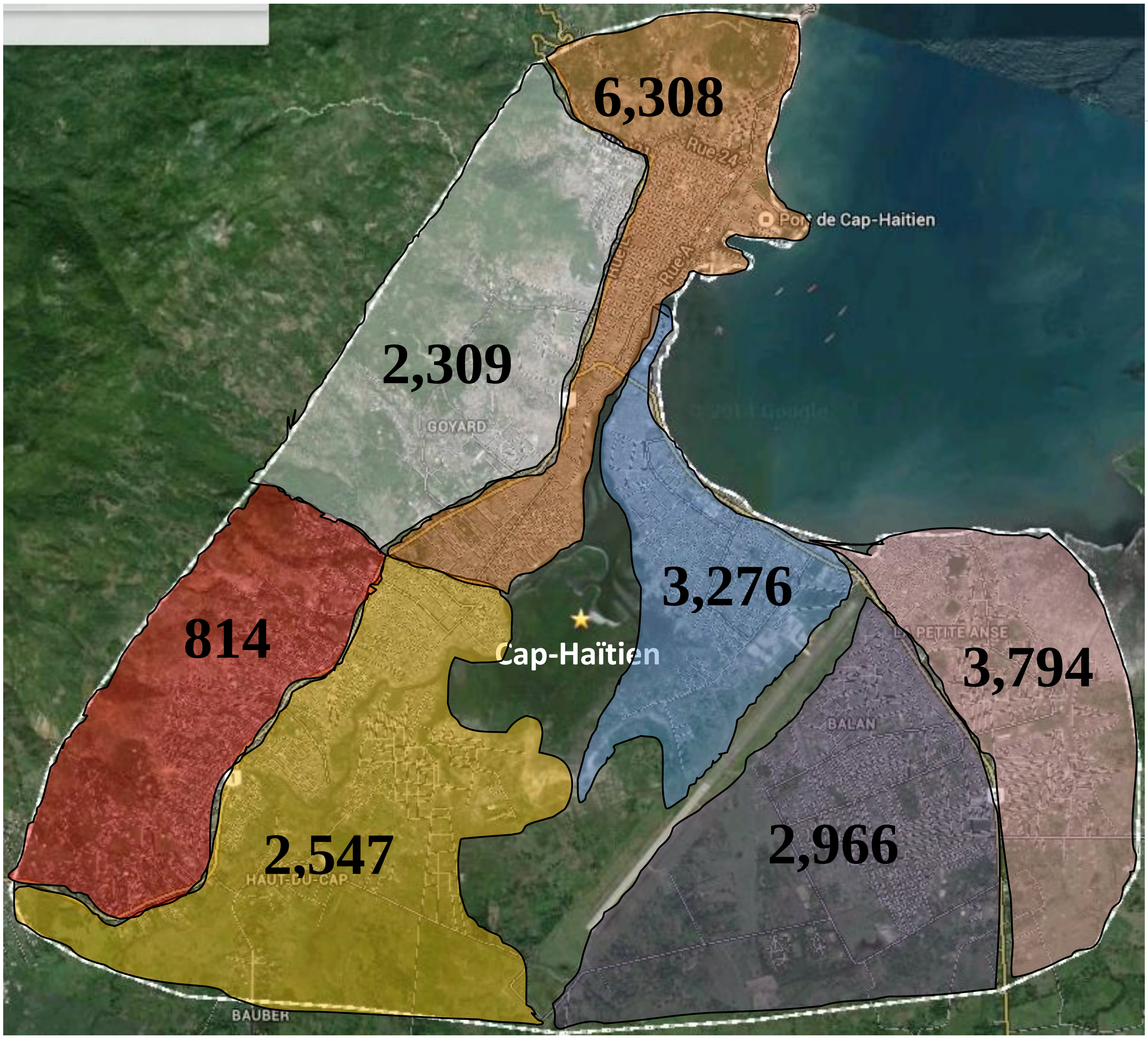

Figure 14. Map visual of the city of Cap-Haïtien with estimated household tally per region.

Source: Google Maps

5.2.1.1.3 Use phase

In this system, the use phase is composed of the operations performed in the composting facility. After solid waste is collected and transported into the facility, drums are manually emptied into compost bins as shown in Figure 15. During the 6 months of treatment, pathogens are eliminated by a combined effect of elevated temperatures inherent in composting, the addition of organic materials which further enables its use as a fertilizer, and turning process that homogenizes these effects (WHO, 2006).

Figure 15. SOIL staff dumping solid waste from drums into the compost bins.

Source: Theo Hiutema, 2014

A washing process is performed to allow these drums to be reused in the transporting operations after the delivery of waste to the facility. Diluted detergent and water are used for the washing process; the water is pumped from a well using a mechanical pump and a diesel generator and the detergent is sourced commercially. This process was modeled in two compartments: pumping the water and sourcing the disinfectant. The capacity of the pump and the efficiency of the diesel generator were estimated using data available in the Ecoinvent datasets. A process of pumping water at station was defined with a usage of 0.23932kWh of energy to source 1m^3 of water. The disinfectant solution was assumed to be liquid sodium hypochlorite (NaClO) as this is conventionally used for disinfection of water and sanitation facilities (Nelson & Murray, 2008; Pereira et al., 2008). Processes and materials were put together to define a usage of 0.0127 gallons of NaClO per 1 gallon of water used during the washing stage (Withers, Jarvie, & Stoate, 2011).

Organic material, including ashes, sawdust and sugarcane bagasse, is added to the bins to reduce odor, repel flies, and to enhance the composting process. As these organic materials are waste products from other local activities, the impacts from the extraction and processing of these organic supplements are not accounted.

Personal protection equipment (PPE) is used by the staff that interacts with waste during the collection, deposit, washing and monitoring processes of the operation. This personal equipment includes coveralls, protective latex gloves, rubber boots and protective masks, and has been modeled accordingly. The use of these PPE is dependent of the activity performed; for instance, collection is done every 7 days but monitoring is done every day twice over two months.

After 6 months of treatment, the composted waste can be used as fertilizer to benefit the agricultural sector for farmland and agroforestry. Because the generation of fertilizer is a byproduct of the composting of human wastes, the impacts from the generation and use of this fertilizer need to be allocated accordingly. Benetto et al. (2009) describes three possible scenario approaches for allocation within attributional LCA: 1) The impacts of urine and feces reuse, and the transport to and activities within the agricultural sector are not allocated to the system; 2) Urine and compost are considered as waste and thus have negative impact on the system; 3) Urine and compost have positive impact because they displace the production and transportation of chemical fertilizers. However, there is little to no use of fertilizer in the agricultural sector in Haiti. While the use of the fertilizer yielded from the compost operations could increase the yield of agricultural goods (Joensson et al., 2004; Werner, Panesar, Rüd, & Olt, 2009; Yang et al., 2012), and thus generate other positive and negative impacts in a multitude of dimensions, it will not be offsetting the use of other fertilizers and thus, no associated impact is allocated in this scenario. The emissions associated with composting human waste is modelled using data on open composting of organic waste with natural ventilation issued from Boldrin et al. (2009).

5.2.1.1.4 End of life

It is being assumed that all components of this scenario will ultimately be disposed of in a municipal dump at the end of their functional life. Even though there is a potential for recycling and reuse for some of these components, it is less likely for this to occur since they have been exposed to human waste. In addition, even if components are reused in other applications, it is likely that these will still be landfilled.

5.2.1.2 Flush toilet

Ceramic flush toilets are a common hardware associated with sanitation (See Figure 16). This type of toilet includes a series of fixtures and mechanisms that provides a water seal which prevents malodors from exiting the pipes or pits where wastes are transferred through. Among the methods to operate a flush toilet, the most widely practiced are the pour-flush and the cistern flush. In the pour-flush method, water is required to operate the toilet by pouring it after excretion on the slab fixture. In the cistern flush, a valve in a small cistern is used to pump the water in the bowl and perform the flushing. For both methods, the amount of water may vary depending on the height and the volume of excreta needed to be moved over the water seal. For this analysis, it will be assumed that all flush toilets are conventional units of porcelain with a polymer cover and polymer seat and operated by pour-flush. The water for flushing is assumed to be extracted from three sources: from a well mechanically without tools, reused greywater and collected rainwater. Another relevant assumption will be that 1.6 US gallons (6.1 L) of water are required to flush the toilet regardless of the type, consistency or volume of the excreta deposited. (D. D. Mara, 1985; "US Code - Section 6295: Energy conservation standards," 1994) In addition, it is assumed that there is an average of 3 flushes per capita per day. Lastly, it is assumed that there is one flush toilet per household while large buildings will be assumed to contain three units, regardless of their purpose or size. It is safe to assume this since building codes were not found for Haitian construction and scrutinizing in detail over the demand of specific buildings is outside of this study.

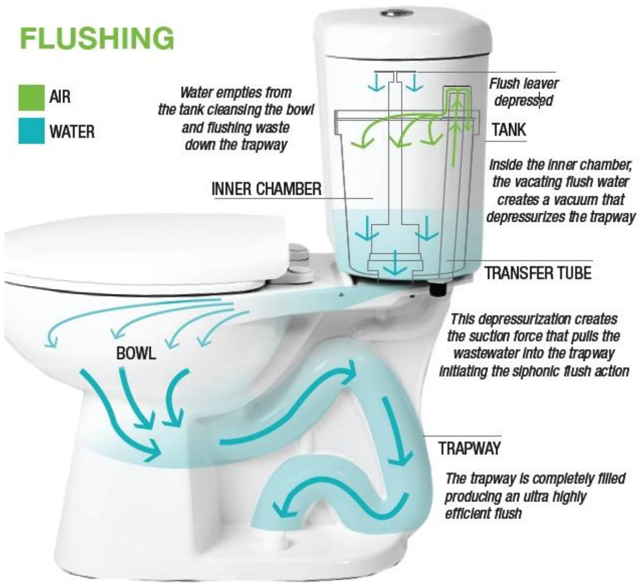

Figure 16. Schematic of a conventional flush toilet.

Source: *http://www.metaefficient.com/toilets/stealth-toilet.html*

After the toilet is flushed, the wastes are transported to a different point for disposal, holding or treatment. For this analysis, two different scenarios of transport and end process will be analyzed: 1) a sewer grid with discharge without treatment, and 2) a sewer grid connected to a wastewater treatment facility prior to discharge.

5.2.1.2.1 Sewer system with discharge without treatment

Sewer systems are a type of infrastructure used to transport wastewater from buildings and other sources to a discharge endpoint. This infrastructure is designed as an underground pipeline network that intakes water streams from a building which is then connected to a municipal sewer network (Refer to Figure 17). Sewer systems are built underground connecting a set of buildings with the purpose of collecting and transporting wastewater to an endpoint.

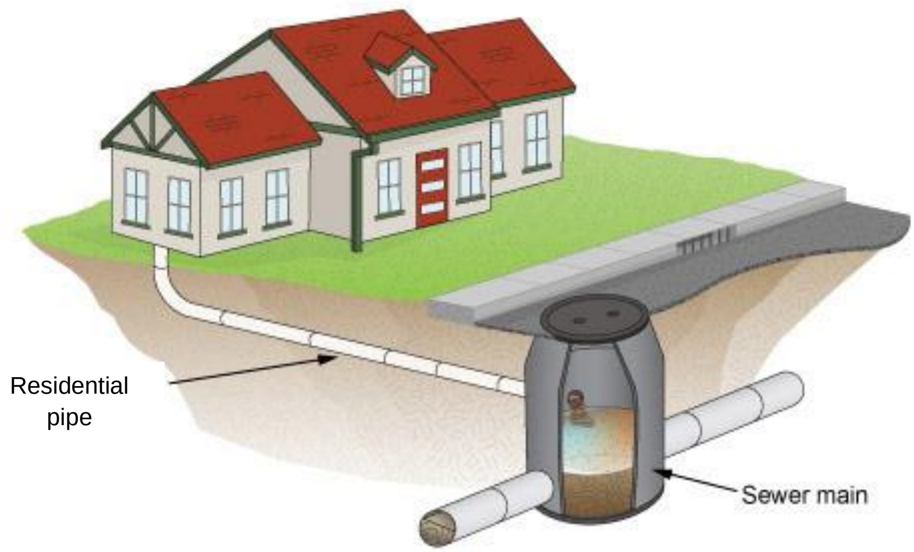

Figure 17. Schematic of a residential sewer pipe connected to the municipal sewer grid.

Source: www.dlsweb.rmit.edu.au

Although different types of sewer systems are currently in use, some have high risks of causing serious environmental pollution problems. For this reason, some countries have regulations that control the type of infrastructure, volume of effluent, and the required treatment of discharge at the household and industrial level (BEA, 2011; EPA, 2004). In developing countries, the fast and unplanned emergence of urban communities often, along with other factors, leaves no opportunity to install sewer infrastructure nor to implement adequate treatment alternatives (D. Mara, 2000; Watson, 1995). In some cases where sewer systems are in place, there is no endpoint treatment to wastewater before it is released into a natural body of water where it is expected to be diluted and dispersed.

In this scenario, a sewer grid system transports the wastes flushed from the household into waterways with no prior treatment. Design and sizing of sewer systems considers a number of factors such as population flow, industrial flow, rain flow, topography, and others. It is out of the scope of this analysis to determine the optimal system or combination of systems that better fit the case study, and so assumptions are made accordingly. The following subsections describe the materials and sub-processes involved in the modeling of this scenario.

5.2.1.2.1.1 Materials and processes

The materials included in this system are: flush toilets as previously defined in this section, residential sewer pipes, and a municipal sewer pipe grid. Residential sewer pipes consist of a set of connected pipes that remove sewage and grey water from a building and into municipal sewer. Residential pipes are currently manufactured from metals or plastics (Refer to Figure 18) to serve different sewer system requirements (SSC, 2008). It was assumed that residential pipes in this scenario are casted from iron based on the expected volume of sewage and the intended application accordingly to conditions described in the case study.

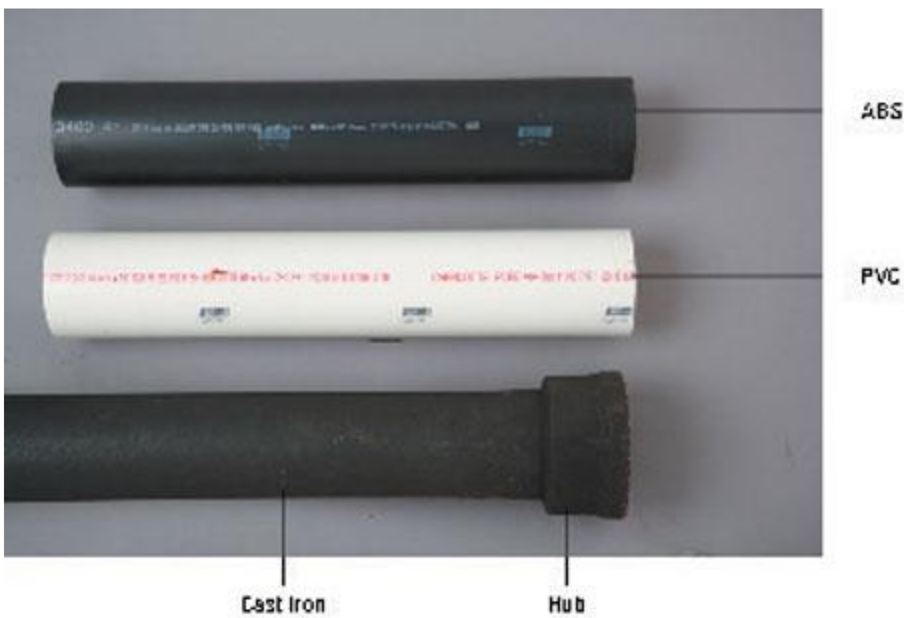

Figure 18. Variety of materials of pipes used in residential sewer drains.

Municipal sewer networks collect wastewater from all buildings tied to the grid and transport it to an endpoint for further disposal. Municipal sewer grids can be designed to transport wastewater alone or to transport both stormwater runoff and sewage in the same pipe. It is assumed that only sewage is being transported by the municipal sewer network. Materials used in this process that are already available in Ecoinvent were used to model both residential and municipal sewer grids (Doka, 2003). In this database, a *Sewer grid*, *class 2* was selected according to the capacities in per-capita equivalents (PCE) (Refer to Table 1). One PCE is representative of the amount of biochemical oxidation demand (BOD) load generated by one person per day in raw sewage (BUWAL, 1996). Similarly, the source *Residential sewer grid* was used to represent sewer infrastructure for residential buildings. Both these entries include the environmental burden of the transport, excavation, installation and dismantling of the pipes used in both types of sewer systems (Doka, 2003).

Table 1. Data for classification of municipal and residential sewer systems per volume of wastewater

Sewer grid capacity class	Meters per captia (Zimmermann et al. 1996:C.15)	Average PCE in class per plant (BUWAL 1994:22)	Million m^3 per lifetime of grid Column 2 * 202 m^3/a * 100 a	Grid length in km Column 1 * Column 2	Kilometer per m^3 wastewater Column 4 / Column 3
1	2.5	233'225	4'711	583	$0.1238 \cdot 10^{-6}$
2	3.4	71'133	1'437	242	$0.1683 \cdot 10^{-6}$
3	4.4	24'865	502.3	109.4	$0.2178 \cdot 10^{-6}$
4	5.7	5'321	107.5	30.3	$0.2822 \cdot 10^{-6}$
5	7.6	806	16.28	6.13	$0.3762 \cdot 10^{-6}$
residential	5.8	–	–	0.087	$0.2871 \cdot 10^{-6}$

5.2.1.2.1.2 Transportation

Default Ecoinvent transportation distances and modes are used for all materials associated with infrastructure. Steel, cast iron, plastics and rubber are assumed to be imported by oceanic fright to Cap-Haïtien and then by truck to the facility. Concrete and gravel are assumed to be sourced locally and transported by truck.

Sewer systems can transport the wastewater by gravity or with a vacuum-pump system depending on the topographic conditions (Gunsaulis, Levings, & Martens, 2009). It is assumed that a gravity based sewer system is in place, and therefore, there is no impact quantified for the transportation of the wastewater.

5.2.1.2.1.3 Use phase

Since it is assumed that wastewater is transported by gravity through the sewer system, there is no need for pumps or vacuum systems. No energy requirements are accounted during the use phase. However, this particular system outputs untreated wastewater into waterways through its use phase. Emissions to water from untreated human wastes were estimated using data from chemical content of human excreta on a developing world diet as published by Schouw et al. (2002) (Refer to Table 2).

Table 2. Averaged generation rate of nutrients in human excreta (urine and feces combined) under a developing-world diet. [2]

Element	Unit	Magnitude
Nitrogen (N)	g/day	6.68
Phosphorus (P)	g/day	1.08
Potassium (K)	g/day	1.68
Sulphur (S)	g/day	0.65
Cadmium (Ca)	g/day	0.762
Magnesium (Mg)	g/day	0.238
Zinc (Zn)	mg/day	8.04
Copper (Cu)	mg/day	1.42
Nickel (Ni)	mg/day	0.236
Cadmium (Cd)	mg/day	0.0432
Lead (Pb)	mg/day	0.142
Mercury (Hg)	mg/day	0.01
Boron (B)	mg/day	0.694

Source: Schouw et al., 2002

Discharge endpoints are assumed considering proximity to population and directional flow of effluent, as well as guidelines from the EPA as possible (EPA, 2004). Figure 19 shows possible endpoints for wastewater discharge without treatment based on the described criteria.

[2] Samples were taken from individuals in Southeast Asia where rice roots, herbs, seafood and pork are staples.

Figure 19. Map location of possible endpoints for wastewater discharge without treatment. Specific locations are represented with the icon

Source: Google Maps

5.2.1.2.1.4 End of life

The end of life considered for this scenario consists of dismantling and replacing infrastructure as it becomes unsuitable for repair. It is being assumed that all components of this scenario will ultimately be disposed of in a municipal dump at the end of its life.

5.2.1.2.2 Sewer system with wastewater treatment facility

An alternative endpoint for sewer systems is the treatment of wastewater. The objective of wastewater treatment processes (WWTP) is to remove hazardous materials and pathogenic agents from wastewater before being discharged to the environment. WWTP can use a variety of technologies to achieve different levels of purification of wastewater and to collect and potentially reuse the byproducts of these processes. In Haiti, these facilities consist of a series of three waste stabilization ponds (WSP) that treat the wastewater through an anaerobic pond, a facultative pond and an aerobic pond (ROH, 2012).

Waste stabilization ponds are a preferred alternative to high-energy WWTP where land is available, the temperature is relatively warm year-round, and there is low supply of skilled labor (Pescod, 1992), thus making it suitable for many regions in the developing world. Similar to sewer networks, design and sizing of stabilization ponds considers a number of factors such as population flow, industrial flow, weather conditions, and others. It is out of the scope of this analysis to determine the optimal system or combination of systems that better fit the case study, and so assumptions are made accordingly. WSP was chosen because it is already being tried in Cap-Haïtien. The objective of WSP is to allow sludge and solid particles in the ponds to settle and later be removed by mechanical processes, and also to create conditions to biochemically eliminate pathogens in wastewater. Floating scum and suspended particles are removed from the pond with the goal of separating as many particles and impurities from the wastewater as possible. According to WHO standards (2006), stabilization ponds are able to output quality effluent that is safe to discharge into the environment, providing a viable large scale sanitation alternative. Because WSP are open structures, bad odors are freely emitted and they should therefore not be located close to housing. Some authorities, like EPA, suggest a minimum distance of 0.5 miles from the nearest housing infrastructure, but it is also suggested that a separation of 0.25 miles and even less may be appropriate depending on wind patterns.

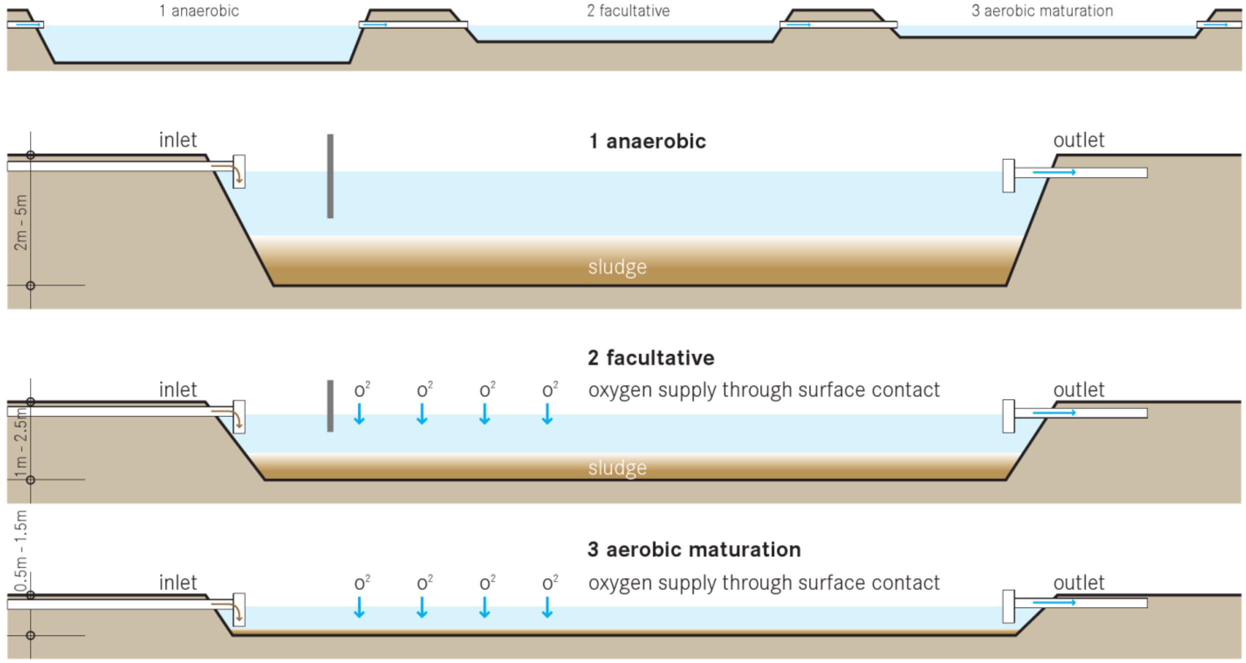

Figure 20. Typical scheme of a waste stabilization ponds: An anaerobic, facultative and maturation pond in series.

Source: Tilley et al, 2008. Compendium of Sanitation Systems and Technologies

The following subsections describe all considerations involved in the modeling of this scenario.

5.2.1.2.2.1 Materials and processes

The materials accounted in this system include: flush toilets, residential sewer pipes and municipal sewer pipes as previously defined in this section, and the infrastructure of the ponds. Materials regarding the infrastructure of the ponds are taken from Ecoinvent database and benchmarked with the literature (Cicek et al., 2001; Machado et al., 2007; Spuhler, 2011) and summarized in Table 3.

Table 3. Materials and emissions inventory for the construction of waste stabilization ponds expressed in terms of 1 population equivalent.

Resources	Unit	Magnitude
Energy		
Petrol	g	38
Electricity	kWh	321.2
Materials		
Steel	kg	24.28
Polyethylene Terephthalate (PET)	g	153.7
Gravel	kg	6.09
Iron	kg	17.7
Sand	g	0.0264
Nickel	g	10.5
Sodium Chloride (NaCl)	g	0.0303
Land occupation	m^2	0.13
Emissions to air		
Carbon dioxide (CO_2)	kg	592
Carbon dioxide, fossil	kg	193
Suplhur oxides (SOx)	g	154
Suplhur dioxide (SO2)	g	78.6
Nitrogen oxides (NOx)	g	118
Carbon monoxide (CO)	g	0.439
Carbon monoxide, fossil	g	68.7
Particulates	g	22.6
Particulates (< 10 µm)	mg	244
Propane (C_3H_8)	g	2.3
Ethane (C_2H_6)	g	3.7
Dinitrogen monoxide	g	72.9
Emissions to water		
Chemical Oxygen Demand (COD)	kg	68.5
Ammonium (NH4+)	kg	4.56
Phosphorus	g	465
Aluminum	g	65
Copper	mg	295
Emissions to soil		
Iron	g	4
Aluminum	g	1.09
General waste flows		
Waste, unspecified	g	2,517
Chemical waste	g	464

Sources: Machado et al., 2007; Spuhler, 2011

5.2.1.2.2.2 Transportation

Transportation distances and modes associated with the sewer infrastructure are accounted as described in the previous subsection. Location for the point of treatment is assumed to be 0.5 miles from the nearest housing at the border of the city as pointed out in Figure 21. In terms of the infrastructure of the stabilization ponds: steel, gravel, PET, nickel and sodium chloride are assumed to be imported by oceanic freight to Cap-Haïtien and then by truck to the facility. Sand and gravel are assumed to be sourced locally and transported by truck.

It is assumed that a gravity based sewer system is in place, and therefore, there is no impact quantified for the transportation of the wastewater.

Figure 21. Map location of possible endpoint for waste stabilization point represented with the icon

Source: Google Maps

5.2.1.2.2.3 Use phase

Since it is assumed that wastewater is transported by gravity through the sewer system, there is no need for pumps or vacuum systems.

Gaseous emissions and effluent are concurrent outputs of this system during its use phase. In general, gaseous emissions from stabilization ponds are composed of carbon dioxide and methane (See Table 4) (Czepiel, Crill, & Harriss, 1993; Suh & Rousseaux, 2002). Effluent is also output from this process and it is able to offset the need for low grade water such as for irrigation (Hunter, Zmirou-Navier, & Hartemann, 2009). However, due to the poor reliability of the overall process and the inherent uncertainty of the effectiveness related to the system's appropriate operation and maintenance, it is assumed that potable water is not an output of this process. The use of byproducts from this wastewater treatment as inputs for agricultural purposes or other activities will not be accounted as major infrastructure and operational changes will need to take place and are out of the scope of this research.

Table 4. Averaged gaseous emissions per capita from aerobic and anaerobic decomposition in stabilization ponds.

	Emissions to air	**Unit**	**Magnitude**
Anaerobic	Methane	g/day	0.1064
	Carbon dioxide	g/day	97.78
	Ammonia	g/day	1.804
Aerobic	Methane	g/day	2.7
	Carbon dioxide	g/day	76

Source: Czepiel et al., 1993; Suh et al., 2002

5.2.1.2.2.4 End of life

The materials used in the construction phase were considered to last for the whole life cycle of the plants, no replacement being considered for such purpose. The ultimate disposal site for the disassembled materials and wastes was assumed to be a landfill.

5.2.2 Life-Cycle Impact Assessment

The life-cycle impact assessment (LCIA) aims to link each item from the LCI to potential human health and environmental impacts. In addition, the resulting linkage models that are used within LCIA are useful for relative comparisons as they classify and characterize environmental impacts within specific ecosystems (land, air, water, human, resources). Existing LCIA methodologies are available to fully describe the cause-effect relations in the items of the LCI and to categorize these impacts at the midpoint or endpoint level. Put simply, a midpoint impact category translates impacts into common environmental issues such as climate change, acidification, human toxicity, etc. while an endpoint impact category translates environmental impacts into damages of concern to human health, the natural environment, and natural resources depletion.

Life-Cycle Impact Assessment methodologies are predetermined characterization and categorization models developed by LCA practitioners and researchers. These methods allow practitioners to uniformly interpret LCIA across reviewed and standardized steps. ReCiPe, a widely used LCIA method, was used to quantify and categorize the environmental burden of the scenarios studied in SimaPro. ReCiPe displays a list of environmental impact categories that are generally used in the LCA realm (Refer to Table 5). The base case for the LCIA is, simply put, a side-to-side comparison of the performance of each sanitation system against the functional unit previously defined. The method *Recipe Midpoint (H) V1.07 / World ReCiPe H* was used for the characterization and definition of impact categories.

Table 5. Environmental impact categories included in ReCiPe.

Impact category Name	Impact category Abbreviation	Unit*
climate change	CC	kg (CO_2 to air)
ozone depletion	OD	kg (CFC-11[5] to air)
terrestrial acidification	TA	kg (SO_2 to air)
freshwater eutrophication	FE	kg (P to freshwater)
marine eutrophication	ME	kg (N to freshwater)
human toxicity	HT	kg (14DCB to urban air)
photochemical oxidant formation	POF	kg (NMVOC[6] to air)
particulate matter formation	PMF	kg (PM_{10} to air)
terrestrial ecotoxicity	TET	kg (14DCB to industrial soil)
freshwater ecotoxicity	FET	kg (14DCB to freshwater)
marine ecotoxicity	MET	kg (14-DCB[7] to marine water)
ionising radiation	IR	kg (U^{235} to air)
agricultural land occupation	ALO	m^2×yr (agricultural land)
urban land occupation	ULO	m^2×yr (urban land)
natural land transformation	NLT	m^2 (natural land)
water depletion	WD	m^3 (water)
mineral resource depletion	MRD	kg (Fe)
fossil resource depletion	FD	kg (oil[†])

Source: ReCiPe 2008 (Goedkoop et al., 2009)

Table 6 and Figure 22[3] show the summary of results of the LCIA for the base case. Climate Change and Human Toxicity are seen to be the within the top 3 most negatively influenced impact categories across all alternatives. Compost Facility is shown to have the least environmental impact in almost all impact categories. This can be mainly attributed to the difference in materials and processes significant inputs required for the infrastructure of the alternative systems. While, sewer systems and waste stabilization ponds require the production, transportation and processing of construction materials such as concrete, cement, reinforcing steel and PET in large quantities, the compost facility scenario makes use of virgin materials in lower proportion and also uses materials that are locally available or that would have been discarded as wastes from other systems. Natural land transformation is the only impact category where the Compost Facility alternative bears a larger impact than the two other; this is due to the fact that most of the infrastructure requiring sewers is built underground and thus allow for reuse of surface land while the compost facility makes use of land with potential for other uses.

[3] This bar graph and subsequent similar have been formatted in a logarithmic scale to allow for better visual interpretation. Raw data has been provided in the List of Tables and Appendix section of this document.

Since both sewer systems and waste stabilization ponds transport sewage through gravity there are no impacts associated with this phase; unlike the Compost Facility scenario where the operation of a truck is required constantly. Sewer systems and waste stabilization ponds bare environmental impacts in different categories. The effects of disposing of untreated sewage in the Sewer Systems alternative are reflected in the significant larger magnitude in the impact categories Human toxicity Freshwater Eutrophication and Ecotoxicity, and Marine Eutrophication and Ecotoxicity.

In Figures 23 - 27 it is shown a comparison of the alternative systems per each life-cycle stage: materials extraction, production, transportation, use, and end of life, respectively. Waste Stabilization Ponds account for larger magnitude in the many impact categories in the materials extraction phase (Refer to Figure 23) because of the relatively large infrastructural needs in terms of volume of materials from non-renewable sources. However, the opposite is shown for the end-of-life phase (See Figure 27) due to the relative higher life-expectancy of the infrastructure compared to both compost facility and sewer systems. In Figure 25 it is shown that the highest impacts are carried by the compost facility and the waste stabilization ponds for the transportation phase. Figure 26 shows how the use phase of the Sewer Systems carry significantly high impacts in the categories Water Depletion, all forms of Ecotoxicity (Human, Marine, Freshwater and Terrestrial), and both Marine and Freshwater Eutrophication.

Table 6. Summary of results for base case (technology comparison).

Impact category	Unit	Compost Facility	Sewer System	Waste Stabilization Ponds
Climate change	kg CO2 eq	4,554,015.00	809,798,320.00	543,980,780.00
Ozone depletion	kg CFC-11 eq	0.40	18.37	19.39
Terrestrial acidification	kg SO2 eq	34,117.33	1,084,231.60	1,225,195.70
Freshwater eutrophication	kg P eq	1,192.61	2,701,976.30	143,336.33
Marine eutrophication	kg N eq	2,332.04	18,691,989.00	638,771.24
Human toxicity	kg 1,4-DB eq	1,224,872.70	471,639,410.00	106,591,520.00
Photochemical oxidant formation	kg NMVOC	23,791.33	1,536,623.60	1,352,217.20
Particulate matter formation	kg PM10 eq	11,212.32	751,744.77	803,215.64

Terrestrial ecotoxicity	kg 1,4-DB eq	4,111.59	4,786,493.00	162,523.26
Freshwater ecotoxicity	kg 1,4-DB eq	31,596.69	312,703,530.00	13,367,046.00
Marine ecotoxicity	kg 1,4-DB eq	25,381.40	39,312,968.00	6,027,351.10
Ionising radiation	kg U235 eq	681,578.27	55,341,187.00	50,495,005.00
Agricultural land occupation	m2a	1,092,846.80	4,072,151.70	4,704,228.40
Urban land occupation	m2a	36,769.65	6,798,709.30	3,782,766.60
Natural land transformation	m2	756.06	(47,480.98)	4,635.21
Water depletion	m3	6,248,882.90	31,074,069.00	31,221,324.00
Metal depletion	kg Fe eq	244,881.01	152,566,320.00	166,136,270.00
Fossil depletion	kg oil eq	1,085,969.30	104,451,340.00	111,245,220.00

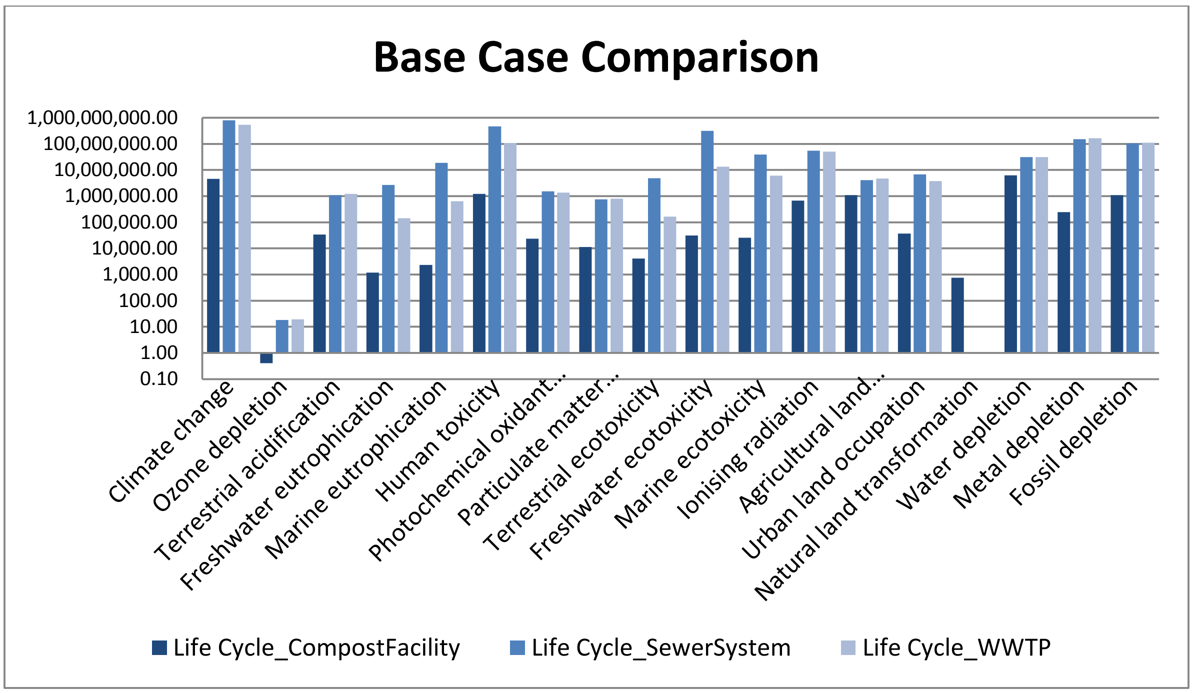

Figure 22. Summary of results of base case (technology comparison).[4]

[4] Refer to Table 5 for units of each impact category.

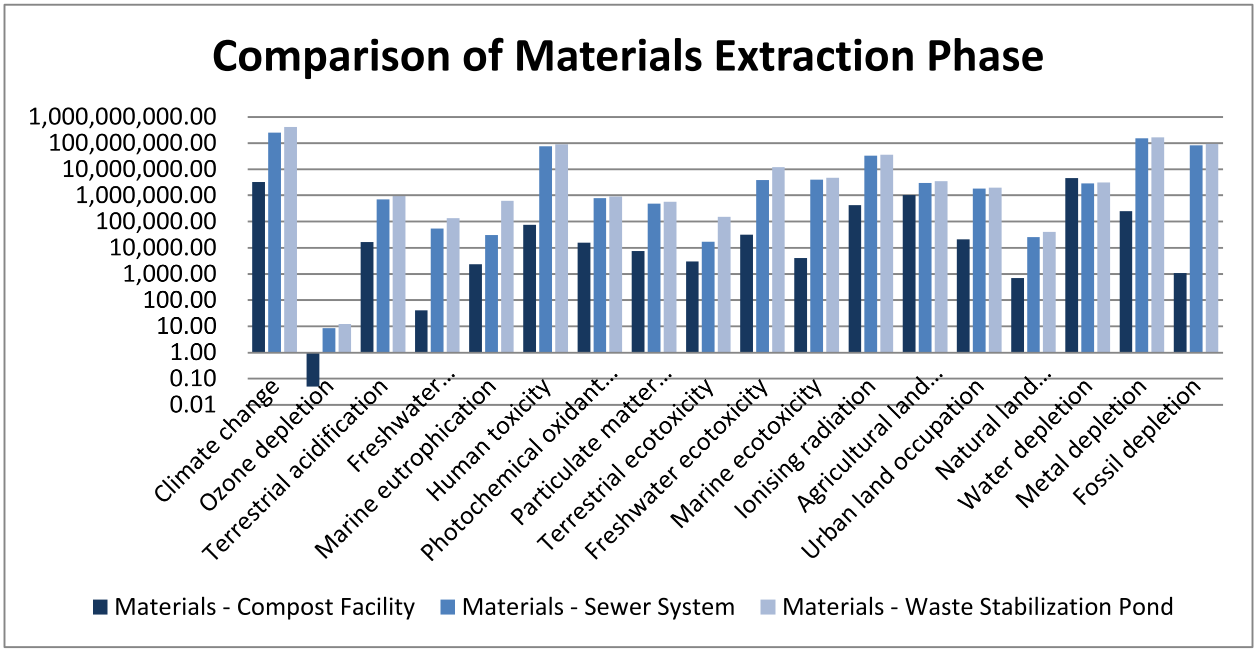

Figure 23. Comparison of LCIA materials extraction phase.

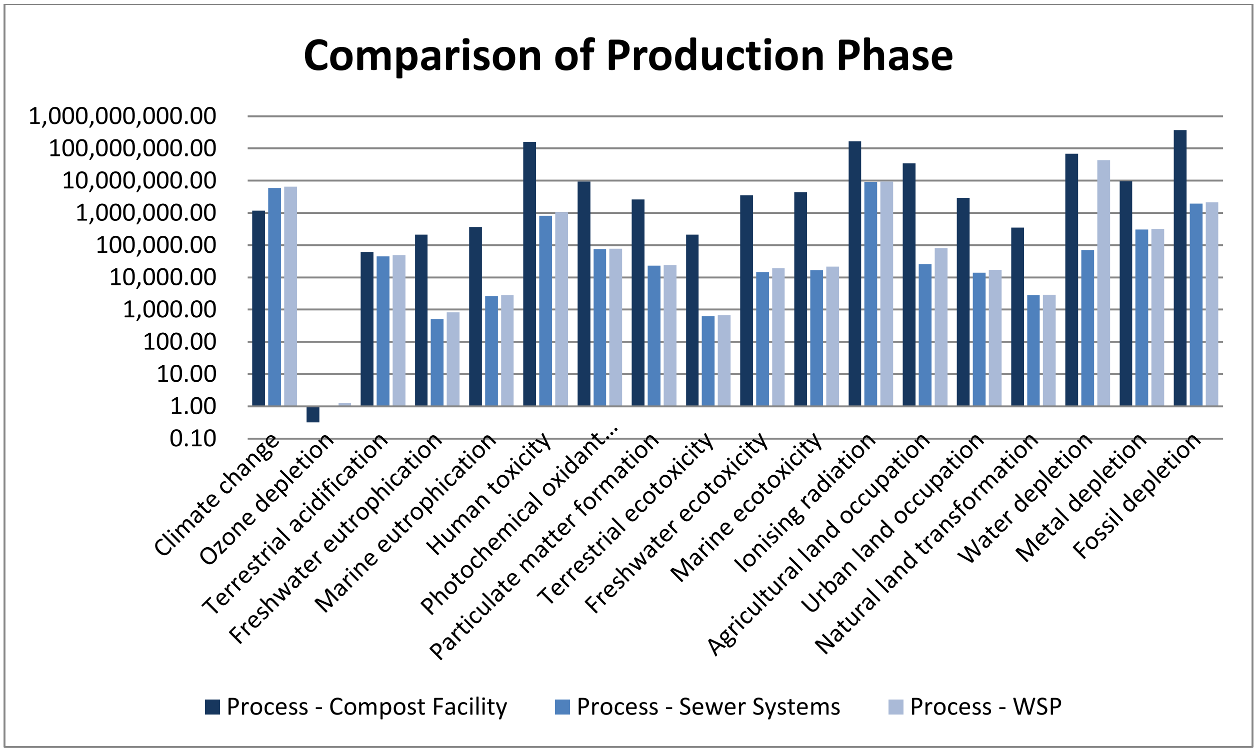

Figure 24. Comparison of LCIA of production phase

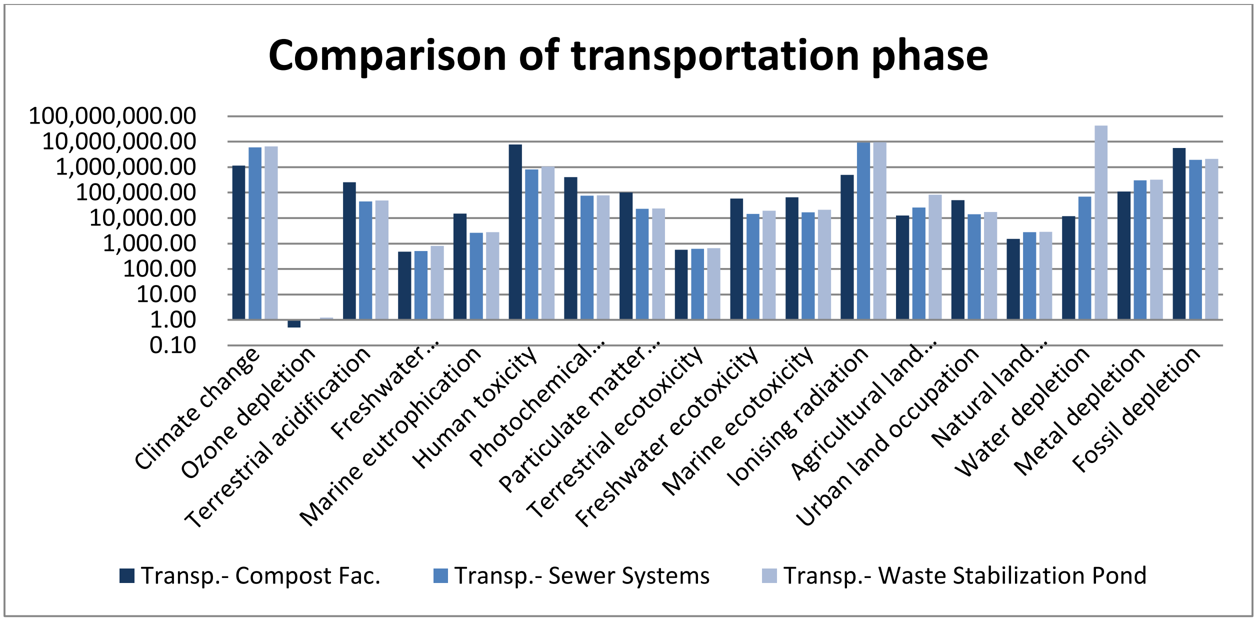

Figure 25. Comparison of LCIA of transportation phase.

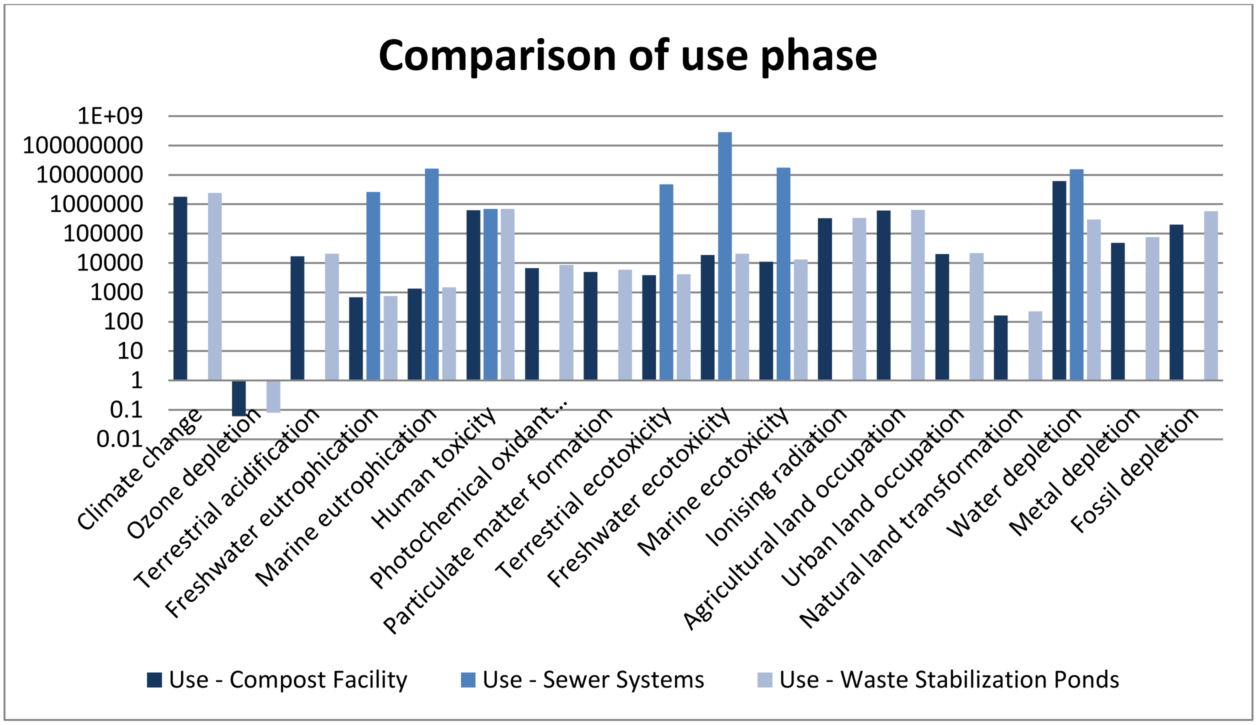

Figure 26. Comparison of LCIA of use phase.

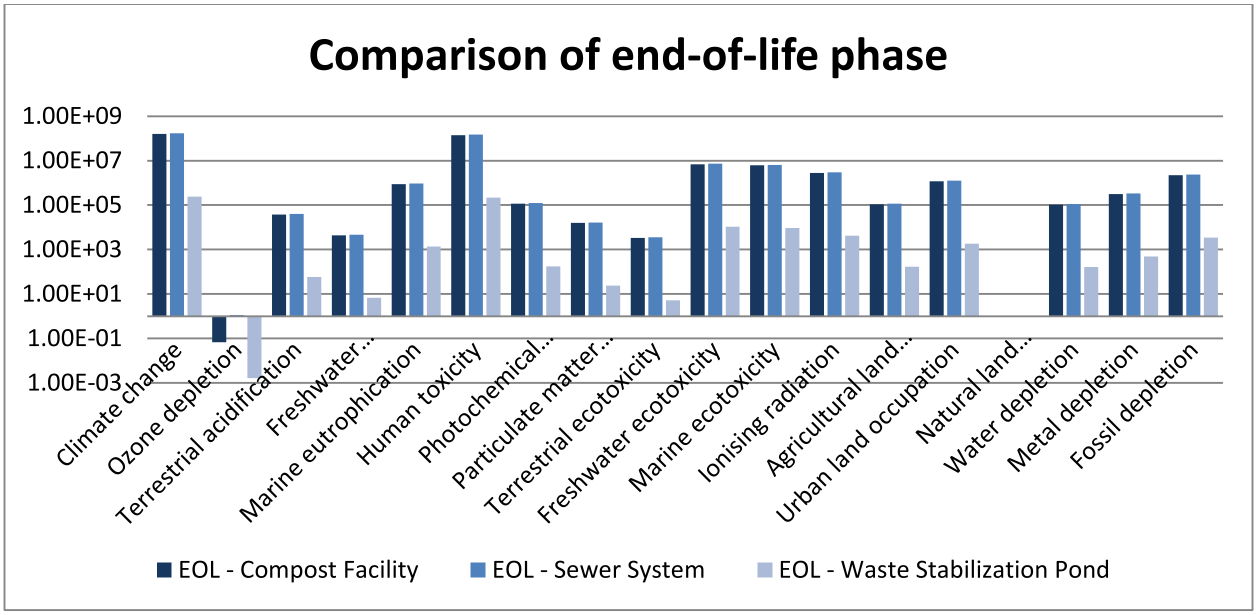

Figure 27. Comparison of LCIA of end-of-life phase

5.2.3 Sensitivity Analysis

Sensitivity Analysis is performed to understand how certain variables affect the output of the model. It is also useful to analyze the uncertainty of the model because large output variability suggests that the uncertainty tied to the parameter value contributes much to the total model uncertainty in relation to other parameters. The parameters presented for analysis are the ones whose altering affects the three alternatives equally among the possible evaluation variables: coverage and population growth over time.

Impact allocation of byproducts, transportation distances and transportation types are additional parameters that could be evaluated. However, it needs to be noticed that neither of these later parameters are common across the alternatives, and thus, will only allow analyzing a sub-model one at a time; this approach is not preferred in order to avoid failing to identify interactions between the sub-models.

5.2.3.1 Scenarios

The following subsections provide an overview of the scenarios that were developed for the sensitivity analysis. These scenarios were developed to help provide some perspective into how the results of the analysis change under various potentially realistic situations. Prevailing conditions in Cap-Haïtien as well as development trends were studied in order to suggest suitable scenarios. Although conducting surveys in target regions of the city could provide the data necessary to accurately build a scenario reflecting the current state, resource restrictions did not allow such approach. Thus estimations were formulated as possible.

The lack of sanitation in Cap-Haïtien, as presented in 5.2.1.1, is highly related to Haiti's lack of infrastructure, the lack of coordination by those institutions intervening in decision making, and the lack of information to make those decisions. R. Kaupp (2006) conducted surveys along with Oxfam on 2005 reporting a distribution of the population of Cap-Haïtien among different sanitation alternatives. However, there have been significant infrastructure and institutional changes in sanitation services over the past years. The effects of the 2010 earthquake, the political instability, the installation of waste stabilization ponds by DINEPA in 2011, and the aggregated results of improvement programs from NGOs, like SOIL and PROTOS are some of the drivers of these changes. Therefore, a reliable source of data regarding the current distribution of sanitation facilities in Cap-Haïtien is not available for analysis so far. In addition, existing household (too small or unstable to allow for an indoor flush toilet or the installation of sewer pipes) and city (lack of roads, agglomeration of households) infrastructure do not allow for complete implementation any of the sanitation systems described in this study. A simultaneous implementation of different sanitation systems with varying coverage is more likely to happen. Under the uncertainty of which sanitation alternative is most likely to be adopted, as there are numerous factors involved that are outside of the scope of this research, the series of scenarios modeled are an attempt to help provide some perspective into potentially realistic scenarios.

5.2.3.1.1 Case 1

Case 1 examines the assumption that the preference for westernized technology has exerted pressure on the installation of sanitary sewer systems. However, only the portion from the more wealthy and touristic areas of the city is being treated at waste stabilization ponds while the rest is discharged into waterways untreated. The remaining of the population in more remote locations is assumed to be serviced by the compost facility.

Table 7. Scenario conditions for case 1.

No. of households	Compost Facility	Sanitary Sewer system (no treatment)	Waste Stabilization Ponds
22214	35%	50%	15%
	7775	11551	2888

5.2.3.1.2 Case 2

Case 2 is an iteration where all waste produced is treated. The high population density, the lack of priority to develop sanitary infrastructure, and the building design in Cap-Haïtien limit the possibility of every household having their own flush toilet connected to sanitary sewer pipes. It is assumed that a larger portion of the households do not even qualify to have flush toilets and sewers, and that urine diversion toilets are a preferred technology in most regions. Due to the relatively low amount of households with flush toilets tied to sewers, a small waste stabilization pond is able to intake all the volume of waste disposed of this way.

Table 8. Scenario conditions for case 2.

No. of households	Compost Facility	Waste Stabilization Ponds
22214	70%	30%
	15550	6664

5.2.3.1.3 Case 3

In the third scenario it is assumed that the vulnerability to environmental and political catastrophes hinder the implementation and function of sanitation systems in the city. In this scenario, it is assumed that part of the waste generated is transported through sewers and is discharged in waterways without treatment while the other portion of households that are not serviced by the municipal sewer grid dispose of waste into the environment which eventually ends in waterways. In the end, all waste generated in the city ends up in the environment without treatment.

Table 9. Scenario conditions for case 3.

No. of households	Compost Facility	Sanitary Sewer system (no treatment)	Waste Stabilization Ponds
22214	0%	50%	0%
	0	11107	0

A summary of the results for each scenario is presented in the following graphs: Figure 28 shows the results for the analysis of Case 1. Similar to the base case; the compost facility scenario projects the least amount of environmental burden in almost all impact categories, while sanitary sewer systems project the largest environmental impact in most impact categories. Similar results can be seen in Figure 29 for the analysis of Case 2. The compost facility alternative has least negative environmental performance compared to WSP in all impact categories (except Natural Land Transformation) in all scenarios.

Other observations can be noted by comparing the results of all case scenarios. In Figure 31 it is shown that the option of no treatment (Case 3) has the worst performance compared to the performance of Compost Facility in the Base Case, Case 1 and Case 2. Moreover, as seen in Figure 33, Waste Stabilization Ponds are only a better option than no treatment in case 1 and 2 where coverage was below 30% of the total population.

Figure 32 shows how the life-cycle of sanitary Sewer Systems is more impactful to the environment in all scenarios considered than to simply discharge with no treatment without investing in much sewer infrastructure as described in Case 3. However, one must be very careful in interpreting these results; while less magnitude of environmental impact is shown for an alternative where sewage is discharged without treatment, there are many other environmental, social and economic considerations that are not captured in this scenario and that definitely need to be taken into account in the context of reality. As stated in the introductory sections of this report, the lack of sanitation systems has important and alarming repercussions in the many layers of natural and manmade systems that motivate the purpose of this study.

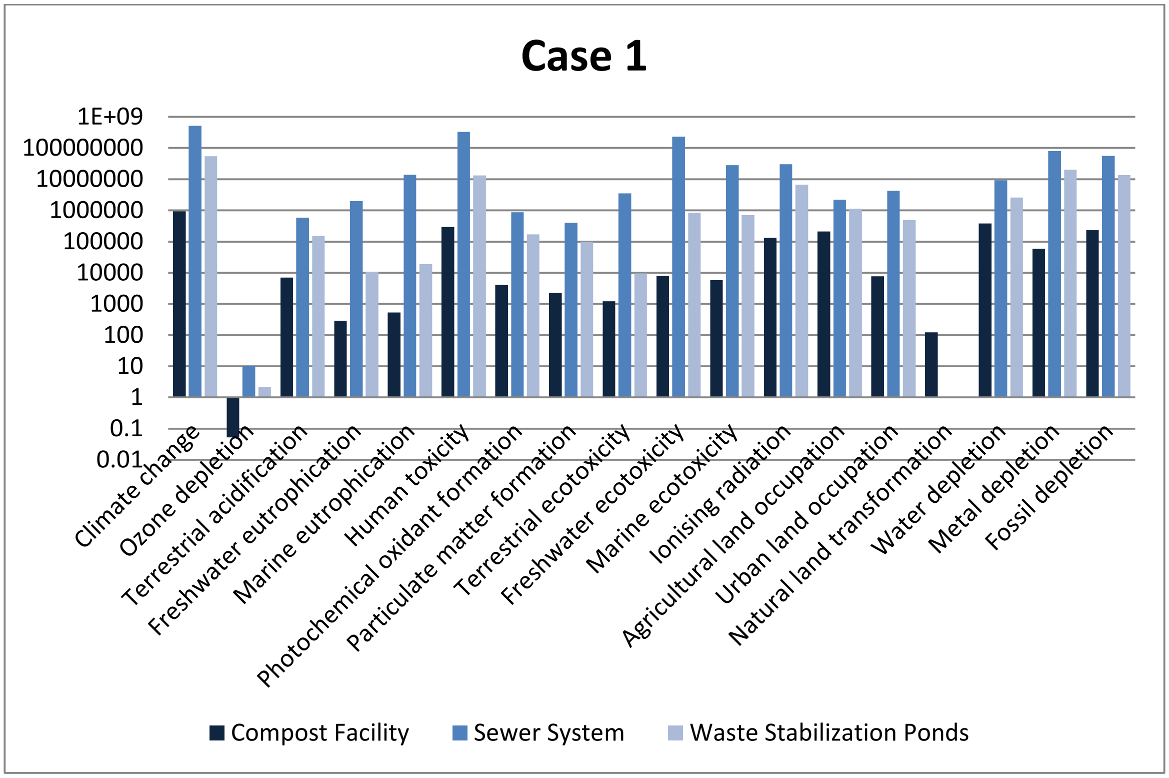

Figure 28. Summary of results of LCIA of parameters in Case 1.[5]

[5] Refer to Table 5 for units of each impact category.

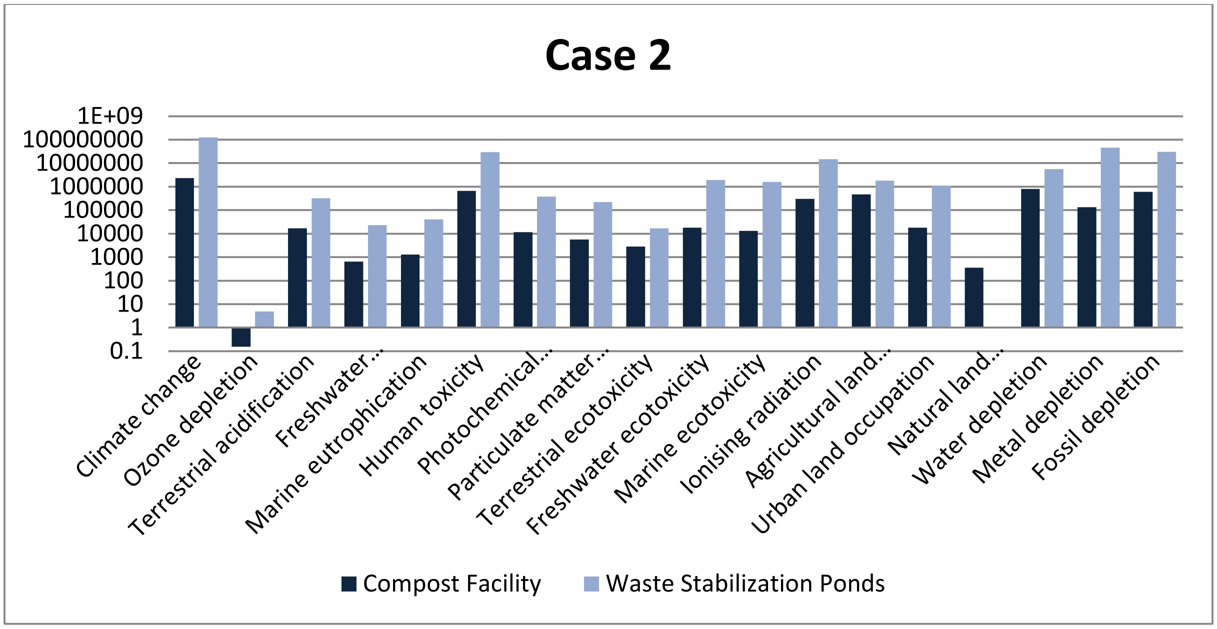

Figure 29. Summary of results of LCIA of parameters in Case 2.[3]

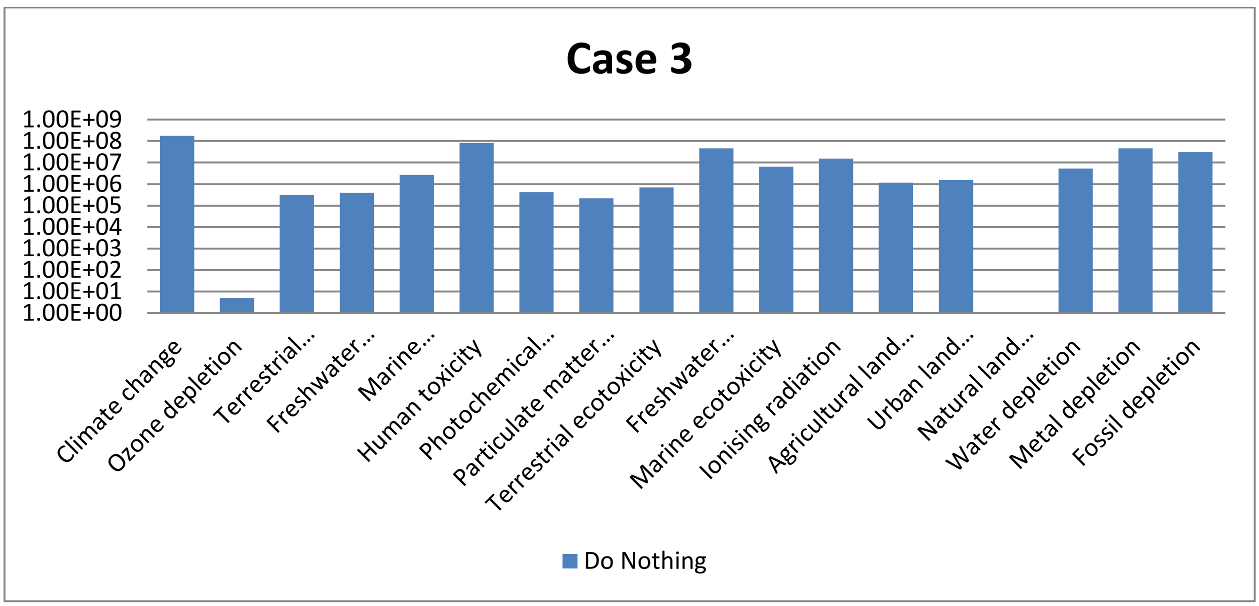

Figure 30. Summary of results of LCIA of parameters in Case 3.[4]

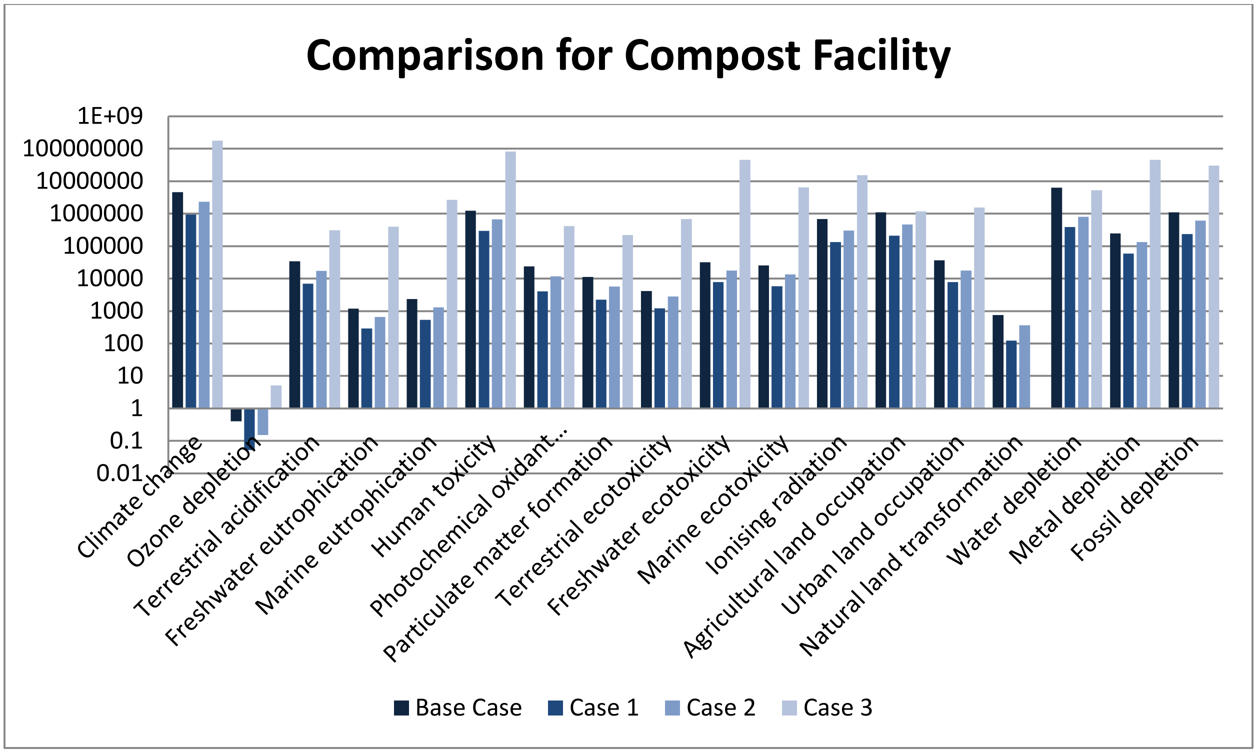

Figure 31. Comparison of environmental impacts of the Compost Facility across scenarios.[6]

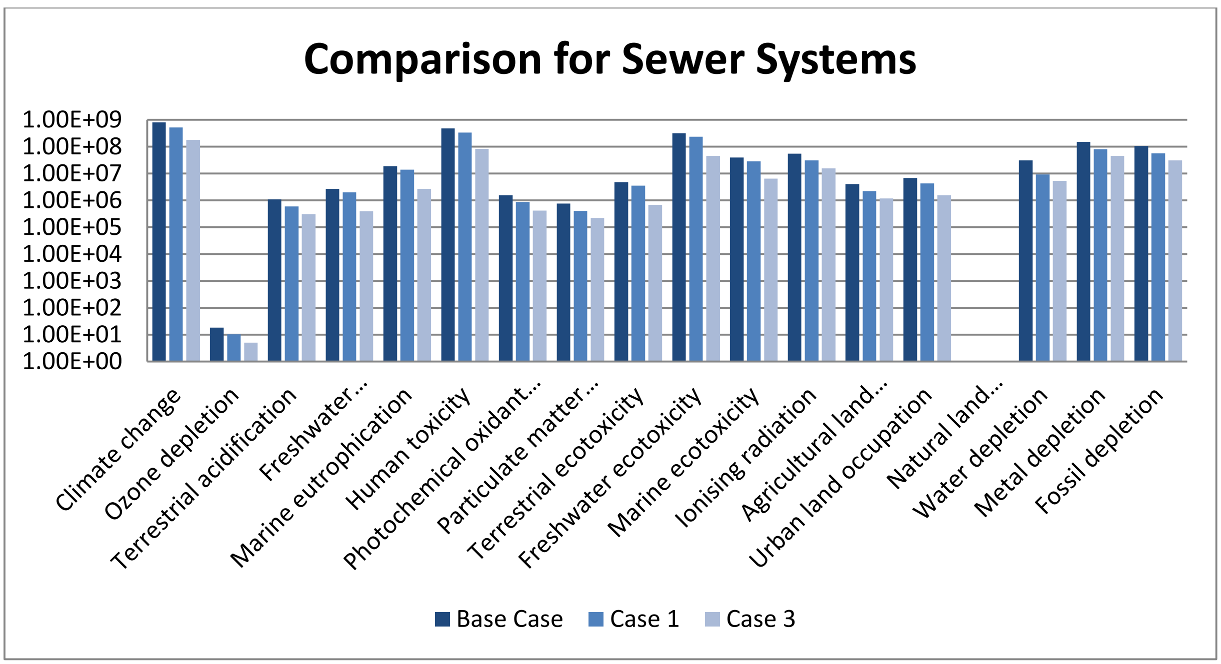

Figure 32. Comparison of environmental impacts of the Sewer System across scenarios.[4]

[6] Refer to Table 5 for units of each impact category.

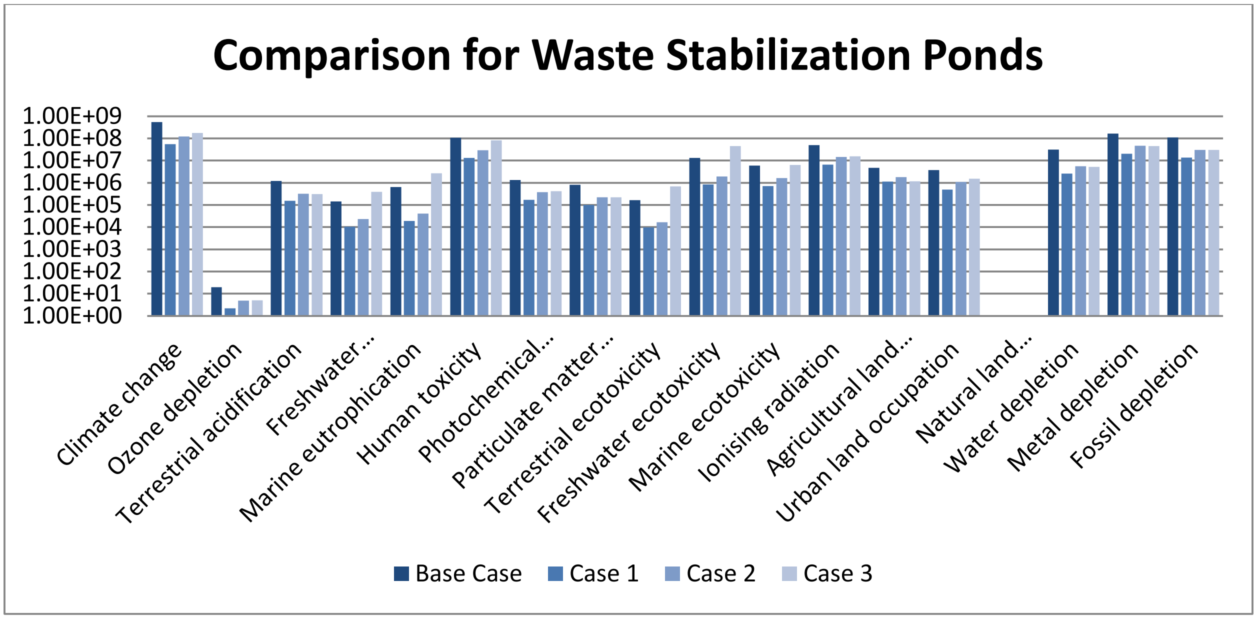

Figure 33. Comparison of environmental impacts of the Waste Stabilization Ponds across scenarios.[7]

5.2.3.2 Population growth over time

Two time horizons are chosen for this sensitivity analysis: 2030 and 2045. Projections of future growth were performed by using historic data from census in Cap-Haïtien (See Table 10) and equation (1). In order to obtain these projections, a growth rate was determined using population index from previous year and equation (2) for growth rate. This method provides an average growth rate for the specified time interval given past and present figures and assuming a steady rate of growth. In this case it makes more sense to use the two more recent time periods. Projections for the two time horizons are estimated to be 207,790 by 2030 and 428,905 by 2045 (with a growth rate of 4.95%).

It is reasonable to assume that population growth will increase the number of households proportionately. However, it is assumed that household infrastructure growth will continue occurring within existing communities eliminating the need for readjusting road or sewer infrastructure significantly, only treatment capacity. This tendency has been addressed in

[7] Refer to for units of each impact category.

published work analyzing the efficiency and feasibility waste management systems under this condition (Al-Khatib et al., 2007; Parrot, Sotamenou, & Dia, 2009).

Table 10. Historic census results in Cap-Haïtien

Year of census	Population
1982	64,406
2003	111,094
2009	155,500

Source: Institut Haïtien de Statistique et d'Informatique (d'Informatique, 2009)

$$Future\ population\ (Pf) = Pr \times (1+i)^n \quad (1)$$

$$Growth\ rate\ (i) = (Pr - Pa)^{\frac{1}{n}} - 1 \quad (2)$$

Pr = Present population (or the most recent data point)

Pa = Past population

n = number of time periods (in years)

Results show that the current infrastructure and operations of both the compost facility alternative and the waste stabilization ponds become less suitable as population increases in projections of both 2030 and 2045. Table 11 and Figure 34 show that the technologies evaluated have different magnitudes of performance across the different categories impact in the projection of population growth to 2030, meaning there is not one obvious best or worst alternative environmentally speaking. Likewise, Table 12 and Figure 35 show a similar trend with projections to 2045. Climate change, Human Toxicity and Metal Depletion are the top 3 most negatively affected of impact categories from all systems in the projection to 2030. While in the projection to 2045, Climate Change and Human Toxicity remain top 2, Fossil Depletion becomes of concern for all alternatives.

Compared to the base case, the alternatives of compost facility and waste stabilization ponds have considerably increased their negative environmental impact compared to the alternative sewer system without treatment. In the case of the compost facility, this phenomenon can be attributed to the fact that changes in infrastructure for the facility, collection (increased trucks, disposable PPE, hygienization, fuel) and treatment are significantly larger compared to other systems. However, improving collection logistics, fuel and size of trucks, and the durability of the materials in the infrastructure could potentially reduce the overall environmental impact of the alternative compost facility over long term projections. Similarly, the increased negative impact from waste stabilization ponds can be attributed to the increase of material and emissions from construction and disposal processes. In contrast, the impact from sanitary sewer systems is directly attributed to the emissions of untreated sewage to the environment.

Table 11. Summary of results of sensitivity analysis for projection to 2030.

Impact category	Unit	Compost Facility	Sewer System	Waste Stabilization Ponds
Climate change	kg CO2 eq	1,068,044,100	462,290,920.00	598,202,710
Ozone depletion	kg CFC-11 eq	134.58	16.04	20.67
Terrestrial acidification	kg SO2 eq	6,600,438.70	1,001,983.90	1,300,126.80
Freshwater eutrophication	kg P eq	92,673.52	566,867.58	170,051.61
Marine eutrophication	kg N eq	431,801.51	3,606,877.40	836,951.55
Human toxicity	kg 1,4-DB eq	103,296,010.00	165,606,270.00	110,786,910.00
Photochemical oxidant formation	kg NMVOC	9,499,453.20	1,283,961.70	1,392,327.30
Particulate matter formation	kg PM10 eq	2,751,174.00	717,645.38	832,735.60
Terrestrial ecotoxicity	kg 1,4-DB eq	513,714.34	931,850.54	208,227.14
Freshwater ecotoxicity	kg 1,4-DB eq	2,720,933.10	63,820,638.00	16,139,176.00
Marine ecotoxicity	kg 1,4-DB eq	3,034,660.90	11,724,194.00	6,295,733.20
Ionising radiation	kg U235 eq	47,510,818.00	49,272,944.00	51,270,759.00
Agricultural land occupation	m2a	50,811,462.00	3,835,065.20	4,800,110.80
Urban land occupation	m2a	3,213,393.30	4,211,446.80	3,836,451.60
Natural land transformation	m2	320,803.12	(17,477.39)	9,616.27
Water depletion	m3	32,263,407.00	18,236,310.00	36,505,358.00
Metal depletion	kg Fe eq	18,086,221.00	151,878,810.00	170,959,720.00
Fossil depletion	kg oil eq	324,488,730.00	99,542,610.00	115,372,830.00

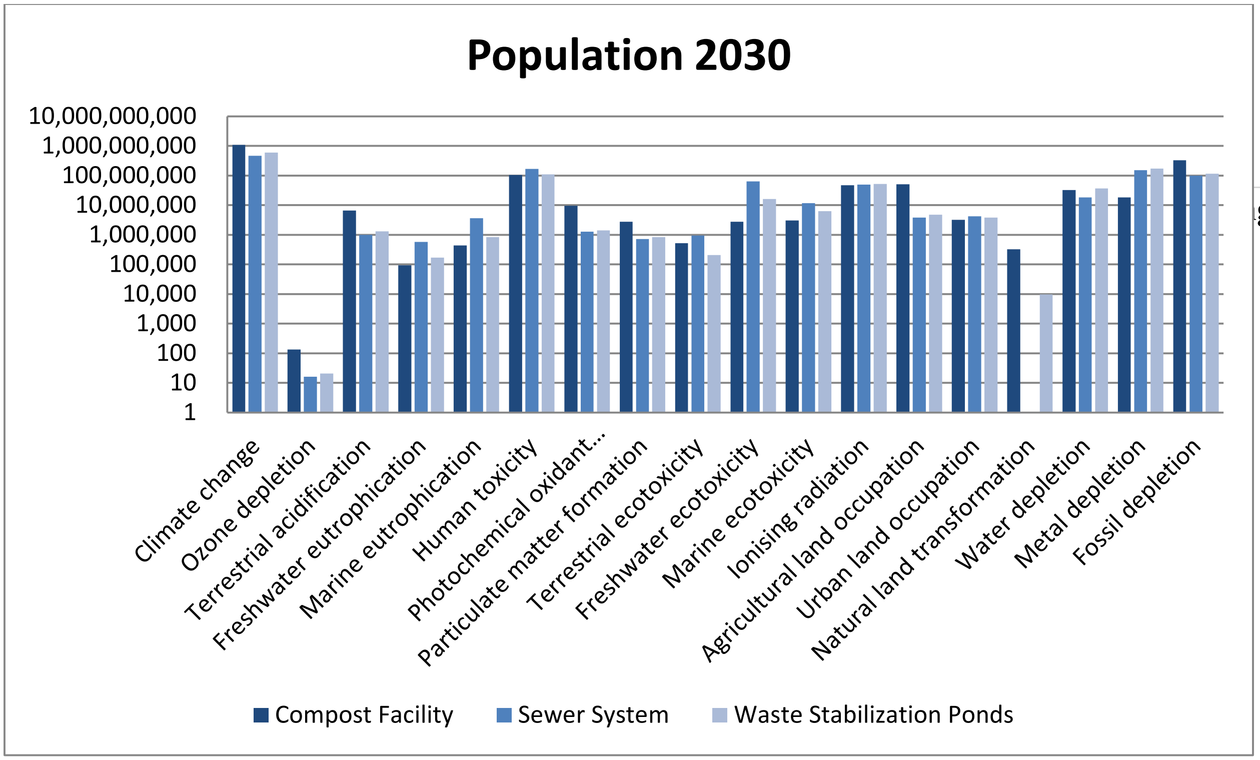

Figure 34. Summary of results of sensitivity analysis for projection to 2030.[8]

Table 12. Summary of results of sensitivity analysis for projection to 2045.

Impact category	Unit	Compost Facility	Sewer System	Waste Stabilization Ponds
Climate change	kg CO2 eq	4,743,297,100.00	549,537,890.00	827,487,120.00
Ozone depletion	kg CFC-11 eq	273.19	16.63	26.09
Terrestrial acidification	kg SO2 eq	34,996,256.00	1,022,633.40	1,616,982.70
Freshwater eutrophication	kg P eq	1,390,580.60	1,102,918.80	283,020.58
Marine eutrophication	kg N eq	2,698,215.20	7,394,221.70	1,674,982.50
Human toxicity	kg 1,4-DB eq	1,431,454,700.00	242,440,490.00	128,527,680.00
Photochemical oxidant formation	kg NMVOC	22,582,033.00	1,347,396.30	1,561,937.90
Particulate matter formation	kg PM10 eq	11,578,628.00	726,206.54	957,564.54
Terrestrial ecotoxicity	kg 1,4-DB eq	6,259,167.00	1,899,616.50	401,491.87
Freshwater ecotoxicity	kg 1,4-DB eq	38,215,889.00	126,306,430.00	27,861,484.00
Marine ecotoxicity	kg 1,4-DB	28,016,816.00	18,650,771.0	7,430,621.50

[8] Refer to Table 11 for units of each impact category.

	eq		0	
Ionising radiation	kg U235 eq	605,331,680.00	50,796,468.00	54,551,133.00
Agricultural land occupation	m2a	932,235,220.00	3,894,589.40	5,205,562.00
Urban land occupation	m2a	36,656,370.00	4,861,018.00	4,063,465.50
Natural land transformation	m2	695,092.30	(25,010.25)	30,679.32
Water depletion	m3	502,319,330.00	21,459,423.00	58,849,579.00
Metal depletion	kg Fe eq	283,127,260.00	152,051,420.00	191,356,330.00
Fossil depletion	kg oil eq	1,246,726,800.00	100,775,020.00	132,826,970.00

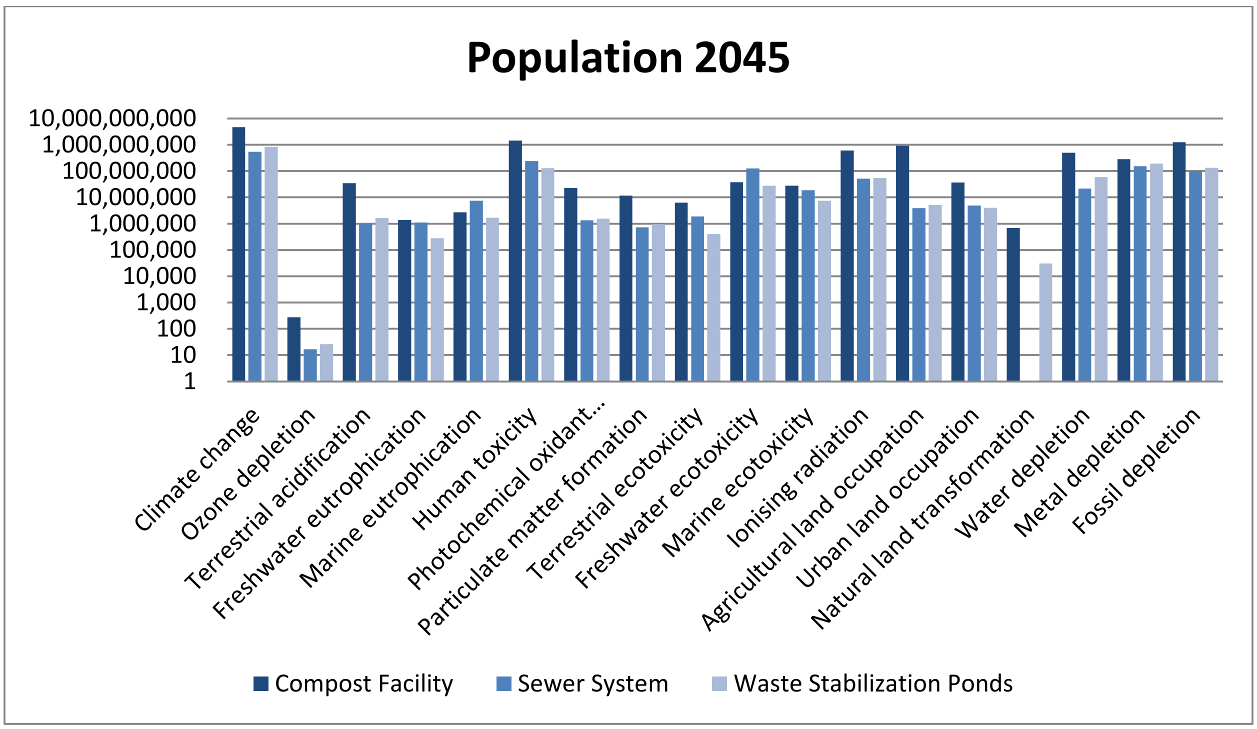

Figure 35. Summary of results of sensitivity analysis for projection to 2045.[9]

[9] Refer to Table 12 for units of each impact category.

5.3 Analytic Hierarchy Process: Prioritization, interpretation and ranking

Based on the evaluation model and results of the LCA, data is collected and organized to formulate a decision model and ranking. A decision model is formulated using Analytic Hierarchy Process steps to evaluate the environmental impact from the life-cycle of three different sanitation systems. With the AHP model, it is possible to simplify and better analyze interrelated decision elements (alternatives and criteria) with the use of a hierarchical structure. In sum, the goal of the decision model is:

To determine a ranking between selected sanitation systems based on their potential for negative environmental impact and accounting for the differing preferences of stakeholders to protect the environment.

5.3.1 Model structure

The purpose of the hierarchical structure is to provide organization for decision makers to perform the decision analysis. It also helps visually display the multiple decision paths available for the decision maker to choose from. By arranging the alternatives and criteria described previously in this chapter, a general hierarchical structure is designed (See Figure 36). The first level of the structure shows the alternatives under evaluation as S*y*. The environmental impacts, and the criteria used for comparison, are indicated as E*x* on the following level.

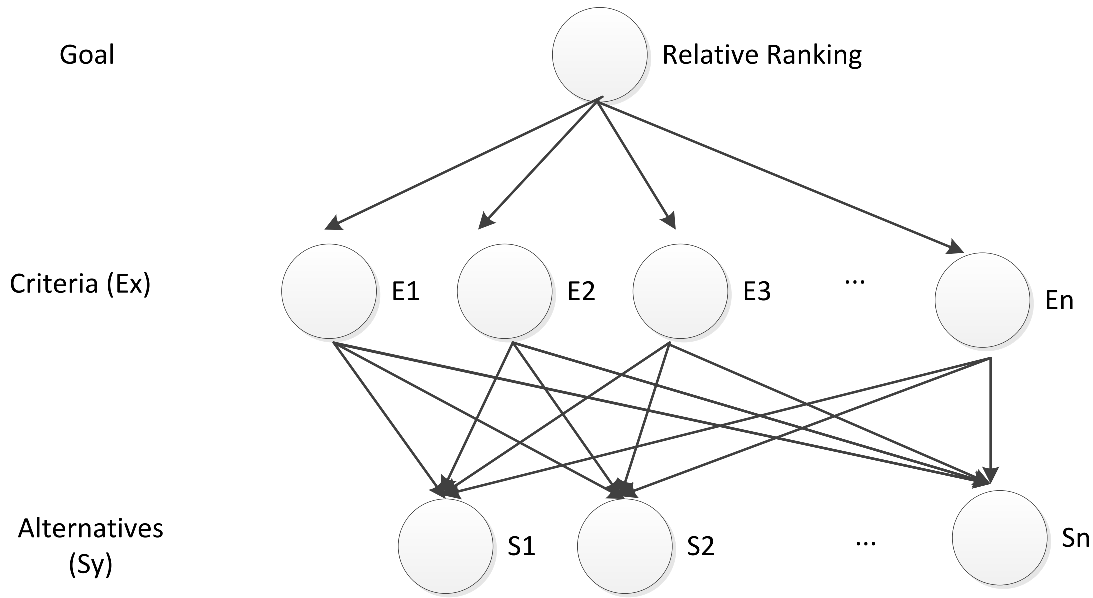

Figure 36. Decision Hierarchy structure for the sanitation systems alternatives under study.

5.3.1.1 Alternatives

The alternatives are simply the different courses of action available to choose from. The goal of any decision making process is to choose one of the possible alternatives by comparing them against each other. In this model, the alternatives to choose from are presented as the sanitation systems formulated in Section 5.2.1 of this document.

5.3.1.2 Criteria

Criteria are a set of standards by which comparisons and decisions are based on. In AHP, each criterion is compared against each other by decision makers to establish their relative importance and to determine their degree of influence on the goal. During this pairwise comparison of criteria, the current environmental conditions and the different biases from stakeholders to protect specific compartments of the environment are accounted for.

In this step, the environmental impact categories from the LCIA are established as the criteria for evaluation in the AHP structure. As stated, the objective of this model is to determine the sanitation system with lower environmental impact, yet impact categories resulting from LCIA affect different compartments of the environment at a different scale. For simplicity and representation, specific impact categories can be segregated when comparing these criteria based on stakeholders' preferences. The next subsection describes an approach to define these specific criteria.

5.3.1.2.1 Priorities

In order to compare the established criteria, preferences need to be defined. These preferences can be determined by a single decision maker, or agreed upon by a group involved in the decision making process. Surveys and behavioral analyses are commonly used to estimate these priorities in MCDA where more than one decision maker are in order. In the case of sanitation in Haiti, potential stakeholders can range from government institutions, international aid organizations, and civil society. In an ideal situation, this step would involve actual representatives from these stakeholder groups who would assess each other, the evaluation criteria, and the alternatives under consideration. Conducting studies to define the individual and overall priorities of these stakeholders is not possible with the available resources for this work. However, given that this is a derived experiment from a case study, it is possible to estimate these priorities by reviewing and interpreting published articles concerning the current environmental portfolio in Cap-Haïtien and in Haiti.

Reports published by the United Nations Environmental Programme (UNEP) on the key environmental conditions for the country suggest that environmental issues include: the vulnerability of Haiti to Climate Change (Gingembre, Hamro-Drotz, & Morton, 2013), respiratory diseases caused by poorly-adjusted engines in vehicles and dust from quarries (Hilaire, George, Brétous, Edouard, & Décembre, 2010), the deterioration of land quality (Gingembre, 2011; Gingembre et al., 2013), the availability of freshwater sources (Gingembre, 2011), and the disposal of sewage and solid waste. A report from 2010 done in conjunction with local Haitian authorities recommend “decision-makers will have to pay greater attention to the state of water resources” and that “Soils must be replenished in order to mitigate the impact of rain and the phenomena of erosion” (Hilaire et al., 2010). A more recent study (Gingembre et al., 2013) on environmental degradation of the Haitian territory inform that overall, the three most important forms of negative environmental impacts are currently seen as deforestation, soil erosion, and degradation of marine environments.

International Institute for Democracy and Electoral Assistance (IDEA) and Organization of American States (OAS), both institutions with goals towards sustainable development published work where the relevance of Cap-Haïtien’s environmental problems in its socio-economic stability was mentioned; specifically, drinking water shortages, poor sanitary conditions in public places, deforestation and erosion, the destruction of the natural habitats of marine resources, and the building developments carried out on arable land were pointed out as major detractors on this issue (Jean-Noël et al., 2010). Similarly, United States Agency for International Development (USAID) has identified the environmental crisis present in Haiti and developed strategies (Adams, 2013; Smucker et al., 2007) to combat specific issues: deforestation, soil erosion, marine ecosystems destruction, and its lack of resiliency to the effects of climate change. A report from Foundation for International Relations and Foreign Dialogue (FRIDE), an European organization with similar goals to the USAID, has concluded issues and strategies (Roc, 2008) alike from other international development organizations.

The research community interested in Haiti’s environmental situation and future has also described concerns for specific issues. A study from Dolisca, McDaniel and Teeter (2007) investigated the perceptions towards deforestation and environmental productivity from over 200 Haitian farmers. The results show that there is more interest placed towards economic objectives than environmental (second in interest) and social objectives. Analysis of the farmers’ responses suggests that drinking water availability and the improvement of soil quality are the top priorities within the environmental objectives. Trevors and Saier (2010) published a summary of recommendations to improve Haiti’s resiliency to disaster such as the 2010 earthquake by investing in infrastructure that focuses on conserving and protecting water resources, as diarrheal and dehydration death rates remain among the aftereffects. In addition, various blog posts from Yves A. Isidor (2001), an Economics professor member from the University of Massachusetts-Dartmouth and spokesperson for *We Haitians, United We Stand For Democracy*, summarize socioeconomic and environmental studies in Haiti up to 2001 and points out that soil erosion and salinity, as well as waterborne illnesses and hazards, are of most priority to attend to in development plans. This is also briefly observed by Myers (1986) who connected the declining soil and water quality in Haiti to its increasing vulnerability to political instability and natural disasters.

In summary, the most recurrent environmental concerns discussed among the reviewed stakeholders' publications are shown to be soil erosion and deforestation. Following, water resources are identified as a priority, specifically the conservation of marine ecosystems and the availability of drinking water. Vulnerability towards climate change and air quality are also discussed but not seen in all the data reviewed. Impact categories as introduced in Table 5 can be selected to represent these specific concerns during the evaluation step of the model.

5.3.2 Model application

After hierarchically structuring the decision model, the next step is the comparative assessment. The elements on the second level (criteria) are arranged into a matrix and the stakeholders proceed to make comparisons about the relative importance of each with respect to the overall goal. In the matrix, the judgments are performed across rows, from top to bottom. A fundamental scale representing the different values of judgment during the comparison is shown in Table 13.

5.3.2.1 Criteria pairwise comparison

Based on the review completed in the previous subsection (5.3.1.2.1) of this chapter, five criteria were identified:

- Climate Change (CC), measured in kg of carbon dioxide (CO_2) eq. to air. The emission of greenhouse gases to the environment brings concern over survival of humans in present environments as marginal temperature changes enhances increase disability adjusted life years (DALY) related hazards like viruses and diseases.

- Photochemical Oxidant Formation (POF), measured in kg of non-methane volatile organic compounds (NMVOC) to air. NMVOC are relevant hazards in air quality as chronic exposure impairs lung function, worsens asthma afflictions, and induces damage to eyes and nose, throat irritation, and chest discomfort.
- Terrestrial Acidification (TA) measured in kg of sulphur dioxide (SO_2) eq. to soil. The decrease of pH of soils due to anthropogenic activity is of high concern to human and ecological interests. TA decreases the capacity of soils to complete proper cycling of nutrients, to act as a substrate for plant germination of many species, and contributes to the loss of diversity of plant species, and thus the rest of the food chain, that cannot adapt to increased acidity.
- Marine Ecotoxicity (MET) measured in kg of 1, 4-Dichlorobenzene (14DCB) to marine water. MET measures the effects of anthropogenic and natural chemicals, materials and activities on marine organisms. MET causes reproductive failure and reduces productivity of marine organisms, and facilitates the transport of hazardous materials to other species, including humans, through bioaccumulation passing on the food chain.
- Freshwater Eutrophication (FE) measured in kg of phosphorus (P) eq. to water. Eutrophication of water occurs when excess of phosphorus and other fertilizing substances promote the overgrowth of vegetation. This in turn results in predation of oxygen and sun light for other species, the growth of bacteria that deters the quality of water, and the severe reduction of fish productivity.

These are chosen for two reasons: they represent environmental issues currently affecting the case under study, and because they cover different general ecosystems as viewed in most LCIA methods (land, water, air, human, and resources). Although many health issues were discussed in the introductory section of this document, there are not any existing impact categories that would accurately represent them, and thus were not included among the criteria. One relevant reason is the disconnection from what is a concern to human and environmental health in industrialized countries (cardiovascular diseases, cancer, etc.)

compared to developing countries (diarrhea, malaria, etc). Using the data collected in the review of priorities (See sub-section 5.3.1.2.1), criteria pairwise comparison matrices were defined and shown in (3).

$$\begin{array}{c} \\ \begin{matrix} TA \\ MET \\ FE \\ CC \\ POF \end{matrix} \end{array} \begin{array}{c} \begin{matrix} TA & MET & FE & CC & POF \end{matrix} \\ \begin{pmatrix} 1 & 3 & 5 & 8 & 9 \\ 1/3 & 1 & 4 & 6 & 7 \\ 1/5 & 1/4 & 1 & 3 & 4 \\ 1/8 & 1/6 & 1/3 & 1 & 2 \\ 1/9 & 1/7 & 1/4 & 1/2 & 1 \end{pmatrix} \end{array} \tag{3}$$

Table 13. Fundamental scale for pairwise comparisons in AHP.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption

Source: Saaty and Vargas (2012) (Saaty & Vargas, 2012)

Following, is the calculation of the *eigenvector* and the *eigenvalue (λ)*. Simply put, this vector is a list of relative weights of the criteria involved in the decision model that allows a relative ranking. To obtain the eigenvector, the elements of each column were normalized, and then each row was averaged. The eigenvector calculated for matrix (3) results is shown in (4). These results determine the relative ranking of the criteria as follows: TA is by far the most important, MET is the second most important, FE follows in the third order, CC and POF are behind respectively in least importance but closely valued.

$$\begin{array}{c} \text{TA} \\ \text{MET} \\ \text{FE} \\ \text{CC} \\ \text{POF} \end{array} \begin{pmatrix} 0.514 \\ 0.284 \\ 0.113 \\ 0.053 \\ 0.036 \end{pmatrix} \tag{4}$$

A Consistency Ratio (CR) is used to verify how consistent the pairwise comparisons have been. Equation (5) is used to calculate the CR. In order to obtain these CR, a Consistency Index (CI) is determined using data from the pairwise comparison matrix (3) and equation (6). By computing these formulas a CR of 0.07 is obtained. According to Saaty and Vargas (Saaty & Vargas, 2012), if the CR is more than 0.1 the judgments are considered inconsistent and arbitrary, which suggests that the pairwise comparisons should be revisited. A CR of 0.1 or less implies that the inconsistencies in judgment are relatively small, and can be accepted

$$CR = \frac{CI}{RI} \tag{5}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

CI = Consistency Index

RI (Random consistency Index) = predetermined value dependent on order of matrix for randomly-generated pair wise comparisons (Refer to Table 14)

λmax = Sum of the product of respective rows in pairwise comparison matrix (3) and its respective value in the priority matrix (4)

n = order of matrix

Table 14. Average random consistency index (R.I.)

N	1	2	3	4	5	6	7	8	9	10
Random consistency index (R.I.)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Source: Saaty & Vargas, 2012(Saaty & Vargas, 2012)

5.3.2.2 Ranking

By summarizing the data collected (Refer to Table 15) in the LCIA (See sub-section 5.2.2) based on the criteria selected for evaluation, pairwise comparison matrixes are defined (7) – (11) for each of the 3 alternative with respect to each of the 5 criterion.

Table 15. Summary table of results from LCIA for selected impact categories[10].

	Compost Facility	Sewer System	Waste Stabilization Ponds
TA	34,117.33	1,084,231.60	1,225,195.70
MET	25,381.40	39,312,968.00	6,027,351.10
FE	1,192.61	2,701,976.30	143,336.33
CC	4,554,015.00	809,798,320.00	543,980,780.00
POF	23,791.33	1,536,623.60	1,352,217.20

TA (7)

	Compost Facility	Sewer System	Waste Stabilization Ponds	Normalized values
Compost Facility	1	7	9	0.790
Sewer System	1/7	1	2	0.133
Waste Stabilization Ponds	1/9	1/2	1	0.077

[10] Refer to Table 5 for units.

MET				(8)
	Compost Facility	Sewer System	Waste Stabilization Ponds	Normalized values
Compost Facility	1	9	4	0.726
Sewer System	1/9	1	1/3	0.074
Waste Stabilization Ponds	1/4	3	1	0.201

FE				(9)
	Compost Facility	Sewer System	Waste Stabilization Ponds	Normalized values
Compost Facility	1	9	4	0.672
Sewer System	1/9	1	5	0.227
Waste Stabilization Ponds	1/4	1/5	1	0.101

CC				(10)
	Compost Facility	Sewer System	Waste Stabilization Ponds	Normalized values
Compost Facility	1	9	8	0.800
Sewer System	1/9	1	1/2	0.075
Waste Stabilization Ponds	1/8	2	1	0.124

POF (11)

$$
\begin{array}{ccc}
 & \begin{array}{ccc} \text{Compost Facility} & \text{Sewer System} & \text{Waste Stabilization Ponds} \end{array} & \text{Normalized values} \\
\begin{array}{c} \text{Compost Facility} \\ \text{Sewer System} \\ \text{Waste Stabilization Ponds} \end{array} &
\begin{pmatrix} 1 & 7 & 9 \\ 1/7 & 1 & 1/2 \\ 1/9 & 2 & 1 \end{pmatrix} &
\begin{array}{c} 0.785 \\ 0.087 \\ 0.128 \end{array}
\end{array}
$$

By a linear combination of multiplying the eigenvector (4) with the normalized values of each alternative in the pairwise comparison matrixes (7) – (11), a decision vector is obtained (12). The preferred course of action would be the alternative with highest relative value within the decision vector (12).

An example calculation for the alternative “Compost facility”: (0.514)(0.790) + (0.284)(0.726) + (0.113)(0.672) + (0.053)(0.800) + (0.036)(0.785) = 0.7590

$$
\begin{array}{cc}
\begin{array}{c} \text{Compost Facility} \\ \text{Sewer System} \\ \text{Waste Stabilization Ponds} \end{array} &
\begin{pmatrix} 0.7590 \\ 0.1219 \\ 0.1191 \end{pmatrix}
\end{array}
\qquad (12)
$$

As seen in the decision vector (12), the alternative Compost Facility is ranked the highest, followed by Sewer System, and lastly, the Waste Stabilization Ponds.

5.3.3 Sensitivity Analysis

One solution to a MCDA may not provide enough information for decision makers to finalize a decision; especially in the context of large-scale systems where impacts are also wide-reaching and there is little room for feasible changes once a decision has been made. Performing sensitivity analyses can be helpful to understand the robustness of a MCDA method and the reliability of its results in order to make a more informed decision. In addition, there are other reasons for conducting sensitivity analysis in the results of a ranking obtained through AHP. For instance, different prioritization in criteria may result in different rankings for the same hierarchy model. This holds more true to cases where preferences come from a group with different opinions.

Sensitivity in AHP has been thoroughly discussed in the literature, as summarized by Bertuzzi (2012). Chen and Matsumoto (2008) categorized different methods to perform sensitivity analysis into three main types: one-at-a-time incremental analysis, probabilistic simulations, and mathematical models. As discussed by Saaty and Vargas (2012) and Bertuzzi (2012), each of these categories have their advantages and disadvantages. The first method, one-at-a-time incremental analysis, is the most popular because of its simplicity and easy implementation regardless on the size of the hierarchy but does not provide such ample perspective of sensitivity compared to the other categories. Probabilistic simulations allow simultaneous analysis on more than one decision element. Simulations are used to arbitrarily change all weights simultaneously and to explore the effect of the entire domain of possible weight combinations on the ranking. However, not all random combinations of weights result in acceptable consistency and thus elements of the distribution of the decision ranking may not be reliably useful in all instances. Mathematical models are a more efficient approach compared to the previous categories because they do not require iterations and their results are verifiable through mathematical formulas. However, mathematical models are only helpful when it is possible to express clear relationships between the input data and the solution. In addition, not all mathematical models are flexible enough to accommodate all arrangements of hierarchy models (i.e.: when there are different number of criteria and alternatives) and most of them are case specific with poor adaptability to other models.

Of these methods, probabilistic simulation offers a more flexible yet structured approach to conduct sensitivity analysis in more than one parameter at a time, and was chosen for this model. The format followed to conduct these simulations were similar to published work by Butler et al. (1997) on sensitivity analysis of the weighs of MCDA models using Monte-Carlo simulations. The results of the Monte-Carlo simulation of the criteria weights are provided in

Table 17 (Refer to Table 16 for summary of simulation conditions).

Table 16. Summary table of simulation conditions.

Variables	Criteria weights for TA, MET, CC, FE, POF
Iterations	1,000
Distribution	Random, multivariate
Range of values[11]	]0,1[

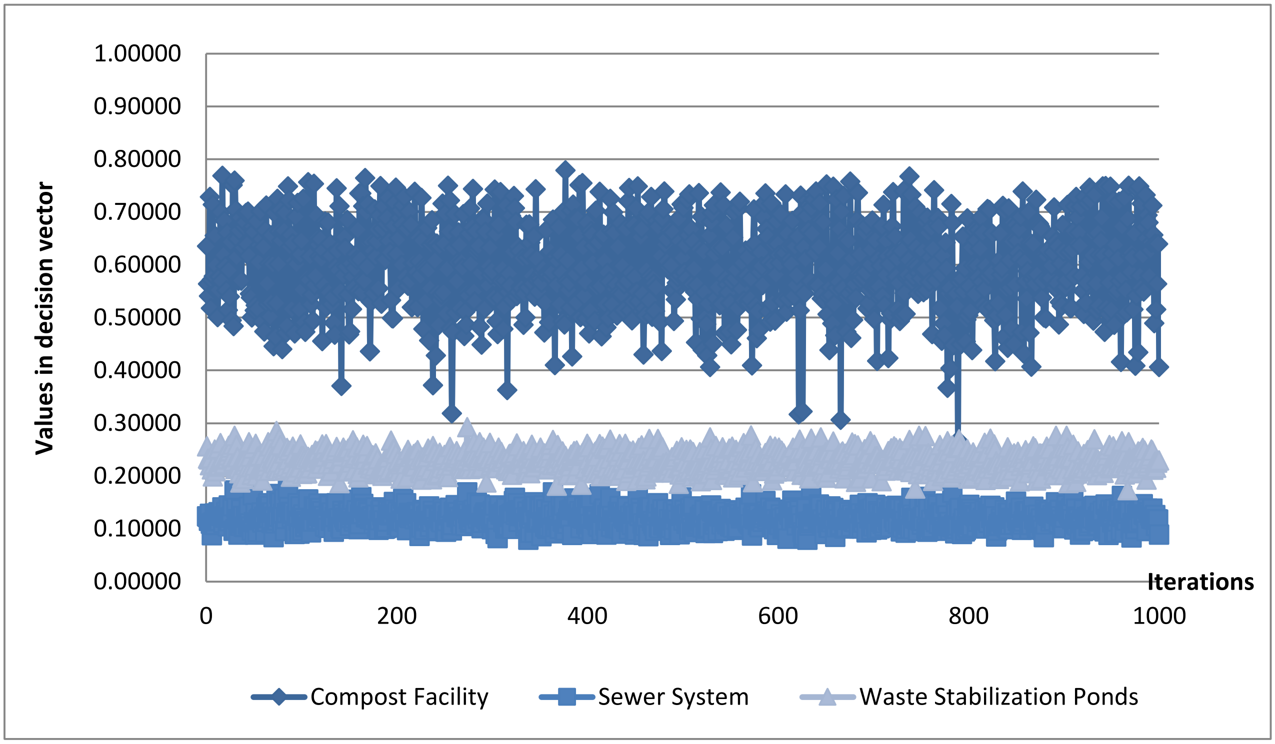

Figure 37. Scatter plot of results of probabilistic simulation.

[11] The range of values is]0,1[with the condition that the sum of the criteria weights is 1 in every iteration.

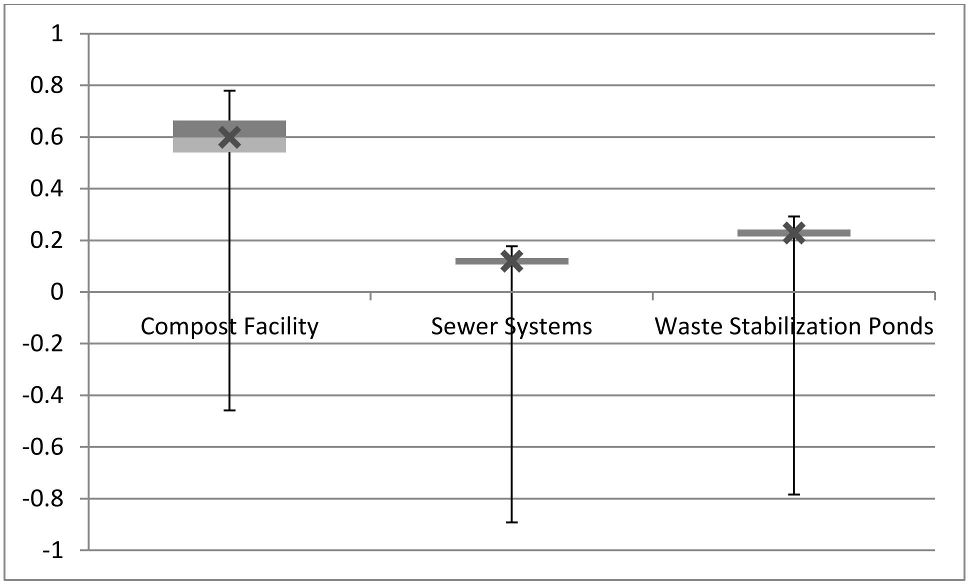

Figure 38. Box-plot graph of summary of results from probabilitic simulations. [12]

Table 17. Summary of results from probabilistic simulations.

	Compost Facility	Sewer Systems	Waste Stabilization Ponds
Minimum	0.267000	0.078959	0.172854
25th Percentile	0.541399	0.107836	0.215701
Median	0.597553	0.120189	0.228460
75th Percentile	0.663940	0.131427	0.241373
Maximum	0.779117	0.177241	0.292437
Mean	0.598602	0.119968	0.228907
Standard Deviation	0.084130	0.016457	0.018379

Several observations can be done from analyzing Figure 37. Based on the simulation results, it appears the original ranking varies upon changes in criteria weight. While the alternative Compost Facility remains as the first option of preference in all iterations, the alternatives of Sewer System and Waste Stabilization Ponds varies according to how the weightings for the criteria are defined. Only in iterations where the weightings for the criteria Marine Ecotoxicity (MET), Photochemical Oxidant Formation (POF) and Terrestrial Acidification (TA) are valued the most, the alternative of Sewer System results is the 2nd alternative

[12] The X corresponds to the mean values, the middle box encloses the median values, the bottom and top whisker represent the 25th and 75th percentile respectively, and the end points are the minimum and maximum values.

preferred (95% of iterations). Otherwise, in the majority of the iteration s the alternative of Waste Stabilization Ponds becomes the 2nd preferred alternative. By comparing the descriptive statistics of both alternatives, as summarized in Table 17, the alternative Sewer Systems has a higher probability of ranking the least preferred choice than Waste Stabilization Ponds. The results of this sensitivity analysis reveal that while the preferred choice (1st in rank) is maintained regardless of changes in criteria weighting, there are around 95% chances that the 2nd and 3rd choices will reverse.

6. Conclusions and recommendations

This study proposed a methodological framework to quantify and rank the environmental performance of large-scale systems deployed in a developing-country setting throughout their life-cycles. The method provides structured steps to compare and contextually evaluate environmental implications of these large-scale systems. A case study on sanitation systems in Cap-Haïtien, Haiti was reviewed to demonstrate and evaluate the framework. Selected sanitation systems were evaluated and various scenarios were modeled to help provide some perspective into how the results of the analysis change in various potentially-realistic situations.

The analysis compared three different sanitation systems: a network of flush toilets connected to sewer systems with endpoints in either 1) waste stabilization ponds or 2) that are discharged into the environment without treatment, and 3) a network of urine-diversion toilets combined with a collection system that diverts waste to an off-site compost facility. The results of this assessment show that the alternative involving the compost facility carries the least-negative environmental burden in almost all impact categories when compared to the other two. It also shows that waste stabilization ponds are only a better option when coverage was below 30% of the total population considered for the cases studied. Discharging sewage without treatment, in all cases, resulted in the largest overall negative environmental impact. However, these outcomes are reversed in projections of population growth for the years 2030 and 2045, where expanding the infrastructure and the capacity to treat waste is needed. In addition, these projections to the future indicate that Climate Change and Human Toxicity are the impact categories that would be most severely impacted in all three alternative systems. A detailed analysis comparing each alternative per life-cycle phase indicates that improvements in collection logistics, size of trucks, and the durability of the materials in the infrastructure could potentially reduce the overall environmental impact of the alternative involving a compost facility over long-term projections.

A ranking of these alternatives was produced through a comparison of selected environmental impact categories considering the differing environmental protection priorities of stakeholders. Results rank the alternative involving the use of urine-diversion toilets and collection to compost facility as the most satisfactory to stakeholders' priorities, followed secondly by the alternative where waste is transported through sewer systems and discharged without treatment and, lastly, the alternative involving sewer systems and an end treatment through waste stabilization ponds. However, sensitivity analysis reveals that this ranking partially changes when priorities seem to change; while the compost facility alternative remains the preferred option, the alternative regarding sewer systems with no end treatment has a 95% chance of becoming the least preferred option. This can be a significant factor for stakeholders and decision makers who would want to consider the sensitivity of this ranking to the many possible changes in valuations to environmental concerns.

In summary, the scenarios and models in this study show that the use of urine-diversion toilets combined with an off-site compost facility is a viable alternative (in terms of environmental requirements) to the lack of sanitation infrastructure and services in Cap-Haïtien, Haiti in the short term. If the durability of the infrastructure is improved, this system also shows promise as a long-term alternative.

7. Future research

The method described in this study is intended to aid international organizations, such as the UN and the United States Agency for International Development (USAID), as well as local organizations in Haiti to understand the circumstances of current sanitation development projects from a large-scale and with a multiple stakeholders' perspective.

There are several opportunities for future work within the methodology proposed and the model developed for the case study. One way to enhance this methodological framework is by developing a dynamic software interface to improve the usability of this tool for users. Moreover, by integrating other economic and social assessment tools to the method can enhance its usefulness as a tool to better evaluate the systems in terms of the Triple Bottom Line of sustainability. It is also of interest to investigate the potential of this methodological framework to assess the sustainability of other large-scale systems in need of advancement in developing countries such as potable water supply, transportation, energy generation and supply, healthcare, and others. In terms of the model for the case study, the variables with relatively high levels of uncertainty could be evaluated in more detail. This can be done by conducting field studies on strategic and representative regions of Cap-Haïtien, and by interviewing stakeholders to extract criteria preferences more reliably. In that same line, the systems under evaluation could be modeled with more granularity and specificity with a wider set of variables. For instance, the AHP hierarchical structure could include all environmental impact categories quantified through the LCA; and furthermore, the LCIA could be improved by defining impact categories that represent the circumstances in developing countries more accurately (as discussed previously over Human Ecotoxicity). Finally, more scenarios for sensitivity analysis could be determined and evaluated in detail to understand more behavioral aspects of the model. Expanding into this future work could enhance the applicability of the methodological framework presented here and open more venue for research.

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9. Appendix

The following appendixes include Information detailing parameters for modeling, sensitivity analysis, process flows diagrams, and expansions of the Life-Cycle Inventory Analysis in some cases.

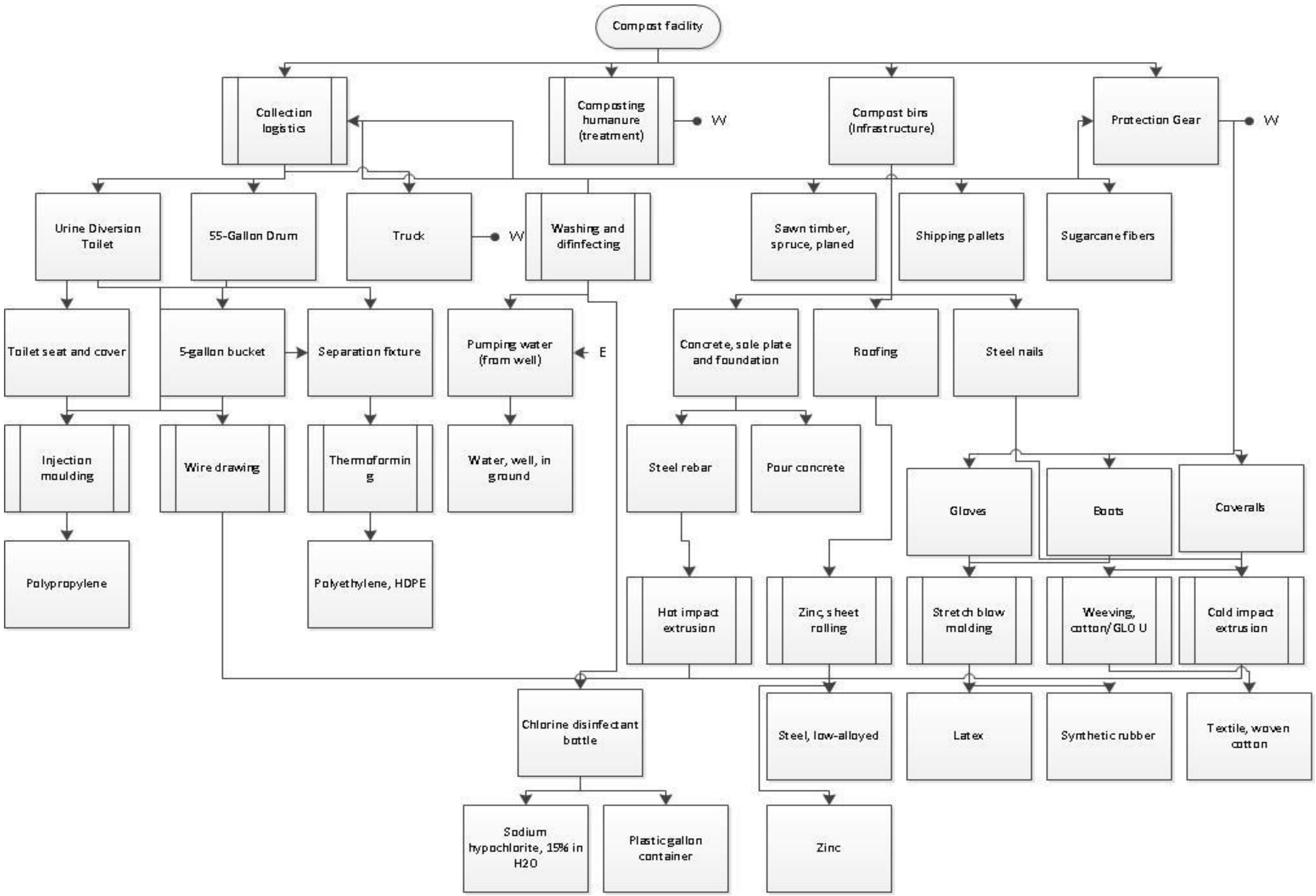
9.1 Flow diagrams of material and processes

Legend:

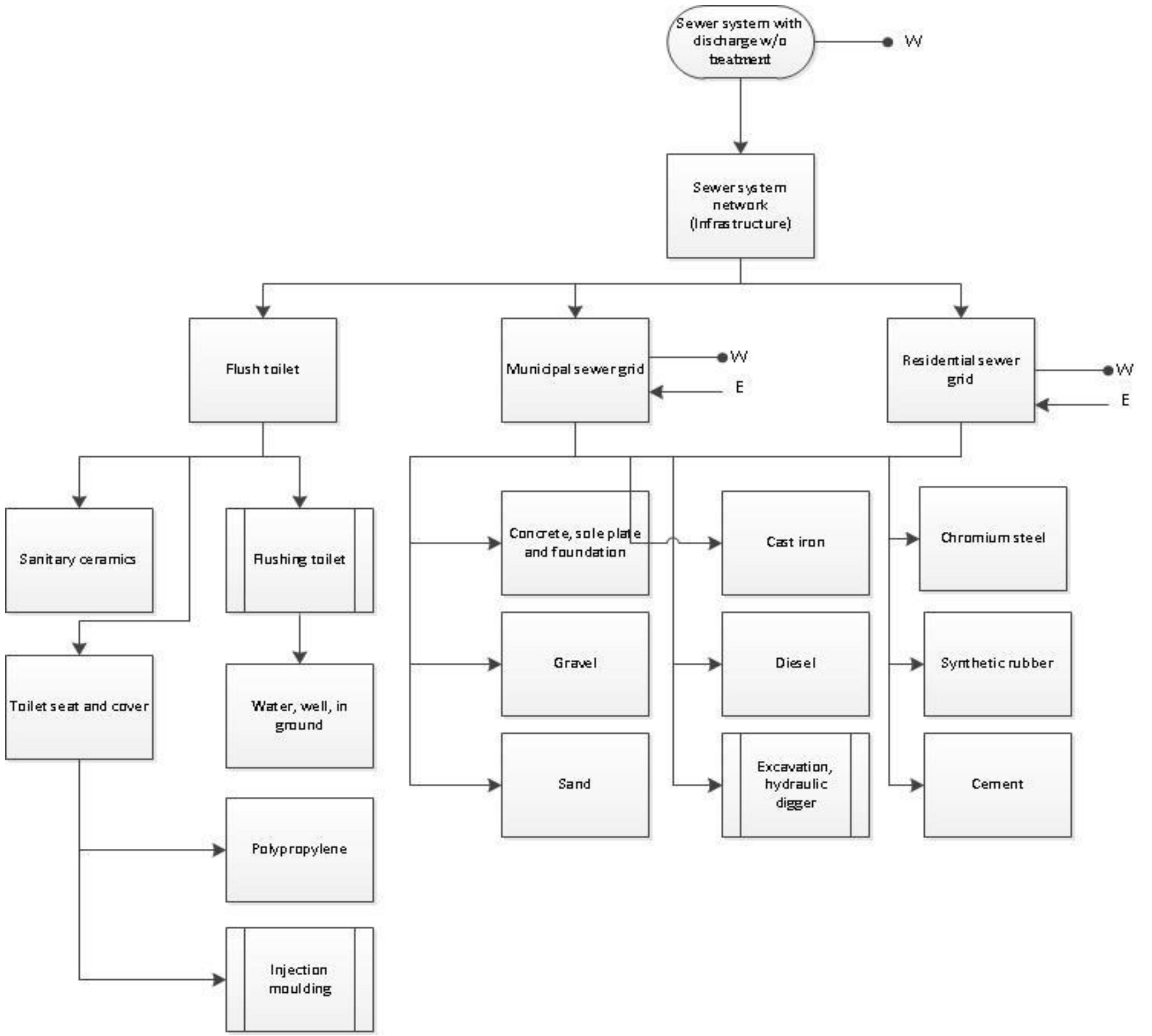
E = Energy

W = Emissions

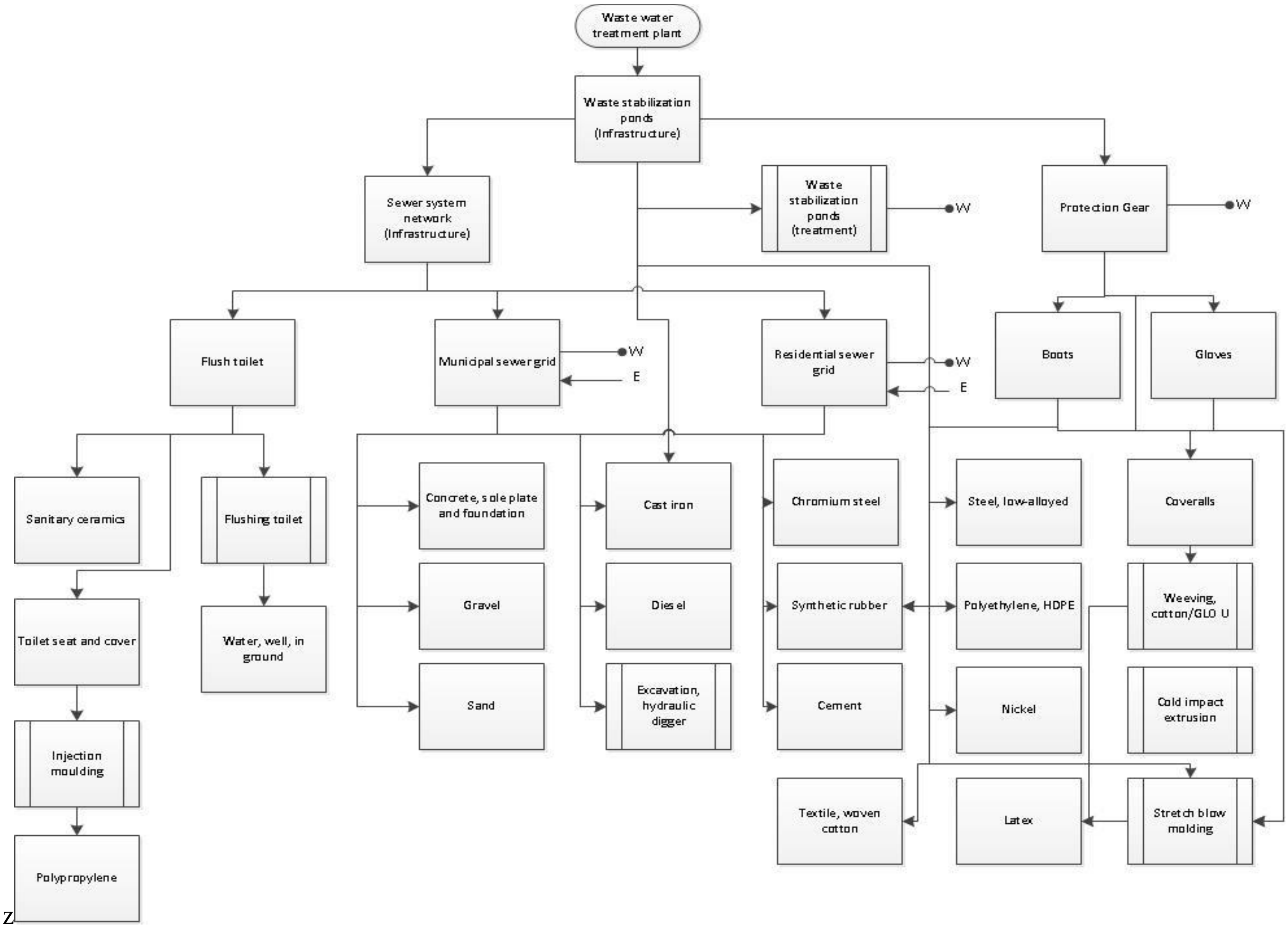
9.1.1 Urine diversion toilet with collection network to off-site composting facility



9.1.2 Flush toilet connected to sewer system with discharge without treatment



9.1.3 Flush toilet connected to sewer system connected to a wastewater treatment facility



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9.2 LCA parameters

9.2.1 Base Case

Sewer System		
# Household	155500	
Flushes per day	3	
Years	15	
Infrastructure	1	1kg is 22,214households
Human Excreta	8.51E+08	1kg is 1 person per day
Flushing toilet	2.55E+09	1kg is 3 flushes per person per day for # of years

Compost Facility		
Population (per capita)	155500	
Years	15	
Infrastructure	2505	tons per person per day / ton capacity for 6 months
UDT	22214	per household of 7 person
Protection gear	50700	for 5 persons per truck per week for # years
Drums	2019	1 drum for each 11 UDT
Washing and disinfecting	1575195	# of drums per 52 weeks per # years
Lorry	13	tons per person per week / 16 ton trucks
Operation Lorry	7.64E+08	Estimated with Google Maps!
Composting	2.98E+08	per person per day per # years

Waste Stabilization Ponds		
Population (per capita)	155500	
Years	15	
Flushes per day	3	
Sewer Infrastructure	1	1kg is 22,214households
Ponds Infrastructure	155500	per capita
Protection gear	54750	for 10 persons per day for # years
Flushing toilet	2.55E+09	1kg is 3 flushes per person per day for # of years
Treatment	155500	per person

9.2.2 Case 1

Sewer System		
# Household	11551	
Flushes per day	3	
Years	15	
Infrastructure	0.52	1kg is 22,214households
Human Excreta	63241725	1kg is 1 person per day
Flushing toilet	1.9E+08	1kg is 3 flushes per person per day for # of years

Compost Facility		
Population (per capita)	7775	
Years	15	
Infrastructure	125	tons per person per day / ton capacity for 6 months
UDT	1111	per household of 7 person
Protection gear	15600	for 5 persons per truck per week for # years
Drums	101	1 drum for each 11 UDT
Washing and disinfecting	78760	# of drums per 52 weeks per # years
Lorry	4	tons per person per week / 16 ton trucks
Operation Lorry	2.35E+08	Estimated with Google Maps!
Composting	14898844	per person per day per # years

Waste Stabilization Ponds		
Population (per capita)	2888	
Years	15	
Flushes per day	3	
Sewer Infrastructure	0.130008	1kg is 22,214households
Ponds Infrastructure	2888	per capita
Protection gear	54750	for 10 persons per day for # years
Flushing toilet	47435400	1kg is 3 flushes per person per day for # of years
Treatment	2888	per person

9.2.3 Case 2

Sewer System		
# Household	0	
Flushes per day	3	
Years	15	
Infrastructure	0	1kg is 22,214households
Human Excreta	0	1kg is 1 person per day
Flushing toilet	0	1kg is 3 flushes per person per day for # of years

Waste Stabilization Ponds		
Population (per capita)	6664	
Years	15	
Flushes per day	3	
Sewer Infrastructure	0.3	1kg is 22,214households
Ponds Infrastructure	6664	per capita
Protection gear	54750	for 10 persons per day for # years
Flushing toilet	1.09E+08	1kg is 3 flushes per person per day for # of years
Treatment	6664	per person

Compost Facility		
Population (per capita)	15550	
Years	15	
Infrastructure	250	tons per person per day / ton capacity for 6 months
UDT	2221	per household of 7 person
Protection gear	35100	for 5 persons per truck per week for # years
Drums	202	1 drum for each 11 UDT
Washing and disinfecting	157519.5	# of drums per 52 weeks per # years
Lorry	9	tons per person per week / 16 ton trucks
Operation Lorry	3.42E+08	Estimated with Google Maps!
Composting	29797688	per person per day per # years

9.2.4 Case 3

Sewer System		
# Household	6664	
Flushes per day	3	
Years	15	
Infrastructure	0.3	1kg is 22,214households
Human Excreta	36485400	1kg is 1 person per day
Flushing toilet	1.09E+08	1kg is 3 flushes per person per day for # of years

Waste Stabilization Ponds		
Population (per capita)		
Years		
Flushes per day		
Sewer Infrastructure	0	1kg is 22,214households
Ponds Infrastructure	0	per capita
Protection gear	0	for 10 persons per day for # years
Flushing toilet	0	1kg is 3 flushes per person per day for # of years
Treatment	0	per person

Compost Facility		
Population (per capita)		
Years		
Infrastructure	0	tons per person per day / ton capacity for 6 months
UDT	0	per household of 7 person
Protection gear	0	for 5 persons per truck per week for # years
Drums	0	1 drum for each 11 UDT
Washing and disinfecting	0	# of drums per 52 weeks per # years
Lorry	0	tons per person per week / 16 ton trucks
Operation Lorry	0	Estimated with Google Maps!
Composting	0	per person per day per # years

9.2.5 Projection for 2030

Sewer System		
# Household	29684	
Flushes per day	3	
Years	15	
Infrastructure	1	1kg is 22,214households
Human Excreta	1.63E+08	1kg is 1 person per day
Flushing toilet	4.88E+08	1kg is 3 flushes per person per day for # of years

Waste Stabilization Ponds		
Population (per capita)	207790	
Years	15	
Flushes per day	3	
Sewer Infrastructure	1	1kg is 22,214households
Ponds Infrastructure	207790	per capita
Protection gear	54750	for 10 persons per day for # years
Flushing toilet	3.41E+09	1kg is 3 flushes per person per day for # of years
Treatment	207790	per person

Compost Facility		
Population (per capita)	207790	
Years	15	
Infrastructure	3347	tons per person per day / ton capacity for 6 months
UDT	29684	per household of 7 person
Protection gear	4204200	for 5 persons per truck per week for # years
Drums	2699	1 drum for each 11 UDT
Washing and disinfecting	2104886	# of drums per 52 weeks per # years
Lorry	1078	tons per person per week / 16 ton trucks
Operation Lorry	6.4E+12	Estimated with Google Maps!
Composting	3.98E+08	per person per day per # years

9.2.6 Projection for 2045

Sewer System		
# Household	61272	
Flushes per day	3	
Years	15	
Infrastructure	1	1kg is 22,214households
Human Excreta	3.35E+08	1kg is 1 person per day
Flushing toilet	1.01E+09	1kg is 3 flushes per person per day for # of years

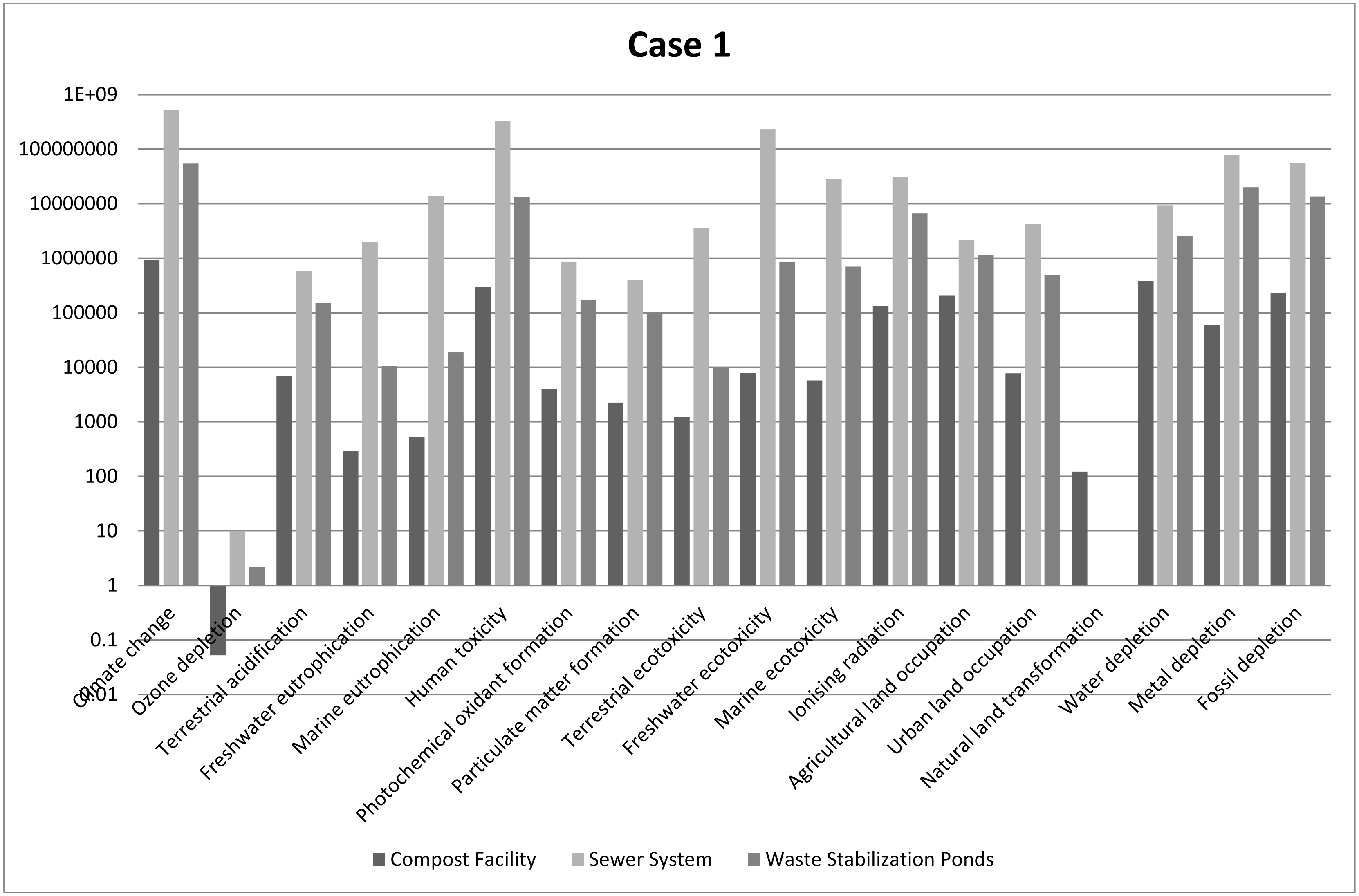
Waste Stabilization Ponds		
Population (per capita)	428905	
Years	15	
Flushes per day	3	
Sewer Infrastructure	1	1kg is 22,214households
Ponds Infrastructure	428905	per capita
Protection gear	54750	for 10 persons per day for # years
Flushing toilet	7.04E+09	1kg is 3 flushes per person per day for # of years
Treatment	428905	per person

Compost Facility		
Population (per capita)	428905	
Years	15	
Infrastructure	13818	tons per person per day / ton capacity for 6 months
UDT	122544	per household of 7 person
Protection gear	78608400	for 5 persons per truck per week for # years
Drums	22281	1 drum for each 11 UDT
Washing and disinfecting	17379008	# of drums per 52 weeks per # years
Lorry	20156	tons per person per week / 16 ton trucks
Operation Lorry	**4.3E+13**	Estimated with Google Maps!
Composting	8.22E+08	per person per day per # years

9.3 LCA Results

9.3.1 Case 1

Impact category	Unit	Compost Facility	Sewer System	Waste Stabilization Ponds
Climate change	kg CO2 eq	926,911.14	516,710,880.00	54,866,826.00
Ozone depletion	kg CFC-11 eq	0.05	10.19	2.17
Terrestrial acidification	kg SO2 eq	6,999.23	586,430.70	151,660.30
Freshwater eutrophication	kg P eq	288.45	1,992,497.20	10,445.06
Marine eutrophication	kg N eq	533.42	13,870,463.00	18,765.35
Human toxicity	kg 1,4-DB eq	295,954.00	329,456,700.00	13,086,093.00
Photochemical oxidant formation	kg NMVOC	4,038.09	868,563.60	169,968.24
Particulate matter formation	kg PM10 eq	2,250.88	400,289.65	99,707.41
Terrestrial ecotoxicity	kg 1,4-DB eq	1,226.50	3,549,571.10	9,629.95
Freshwater ecotoxicity	kg 1,4-DB eq	7,851.82	231,085,310.00	838,313.76
Marine ecotoxicity	kg 1,4-DB eq	5,752.66	28,033,722.00	706,901.65
Ionising radiation	kg U235 eq	132,722.00	30,447,078.00	6,609,024.40
Agricultural land occupation	m2a	209,012.65	2,182,752.60	1,136,546.60
Urban land occupation	m2a	7,782.87	4,247,207.30	493,187.78
Natural land transformation	m2	122.41	(32,945.52)	(855.58)
Water depletion	m3	384,898.95	9,278,091.60	2,568,999.10
Metal depletion	kg Fe eq	58,943.93	79,523,657.00	20,065,232.00
Fossil depletion	kg oil eq	233,577.00	55,665,320.00	13,603,995.00


Case 1
1E+09
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1
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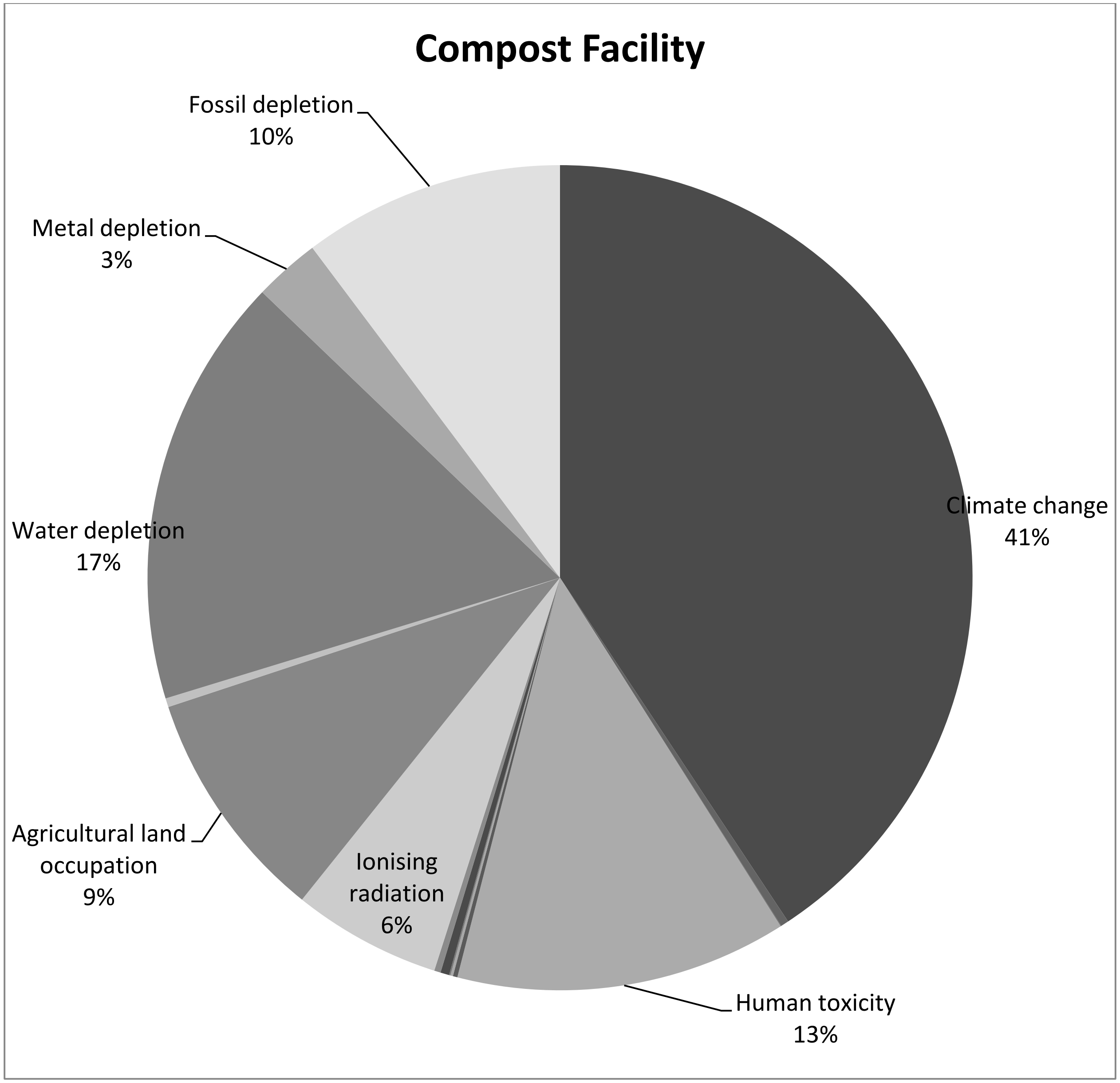
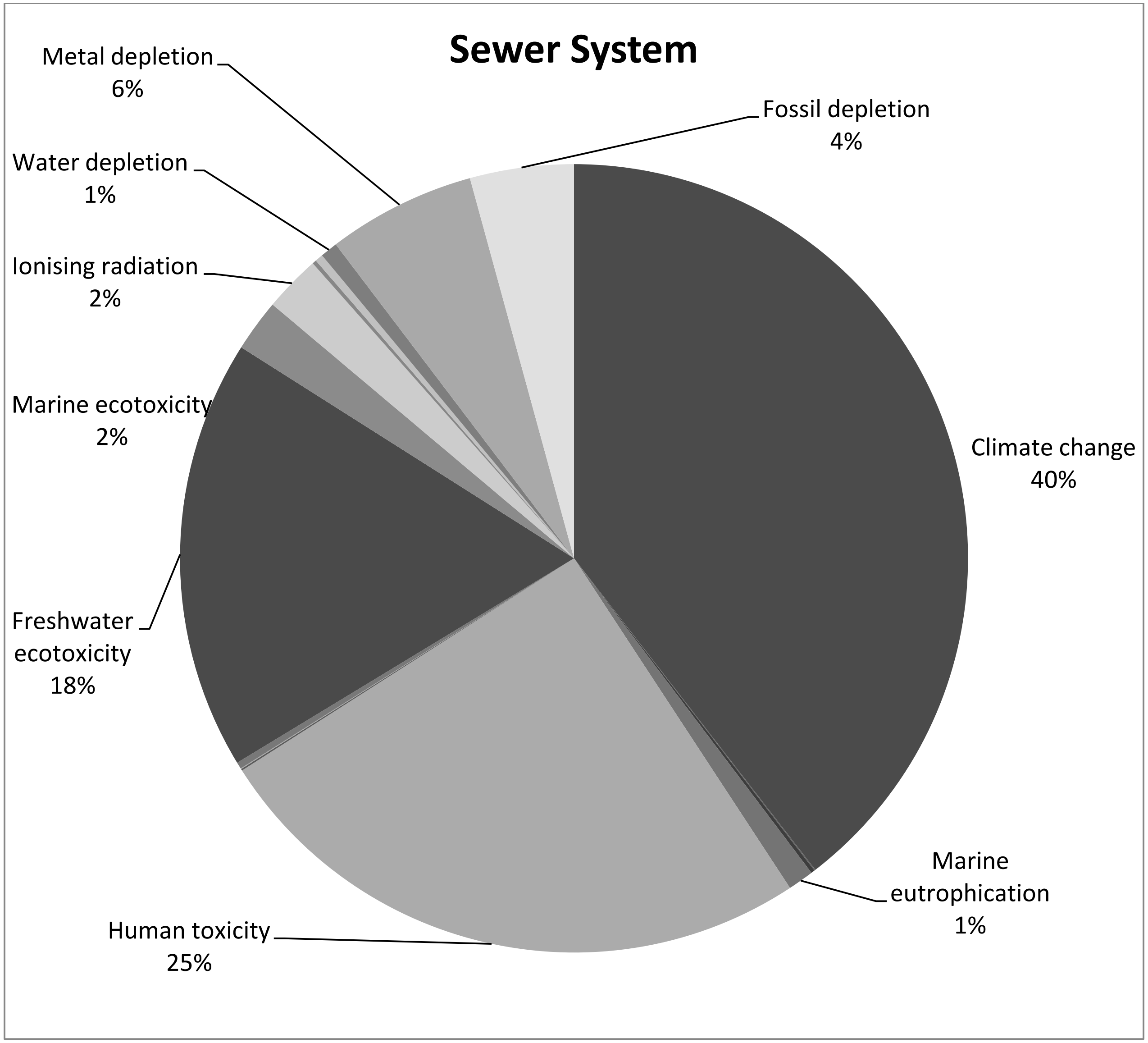
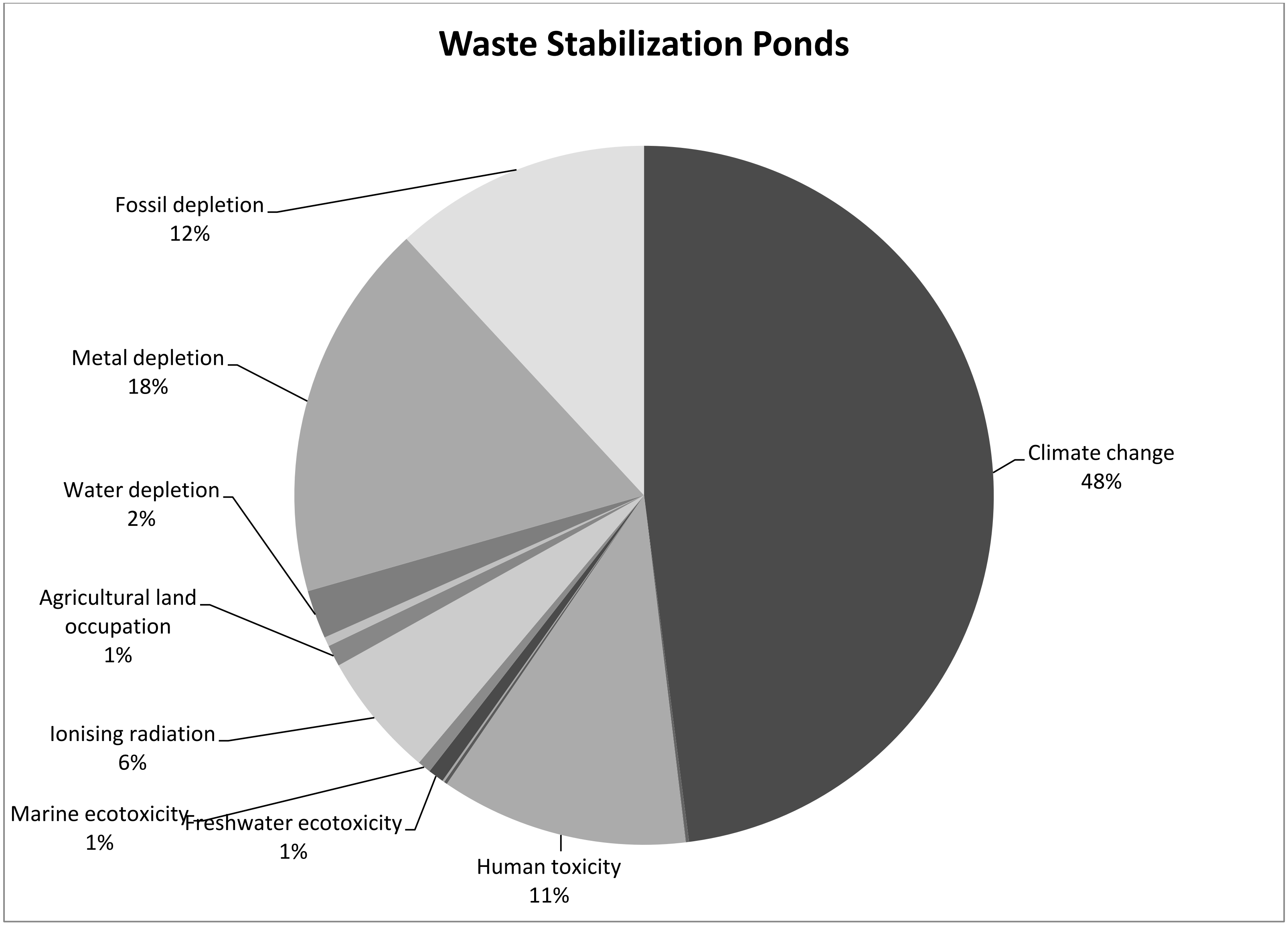
0.01
Climate change
Ozone depletion
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Human toxicity
Photochemical oxidant formation
Particulate matter formation
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Ionising radiation
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion
Metal depletion
Fossil depletion
Compost Facility
Sewer System
Waste Stabilization Ponds

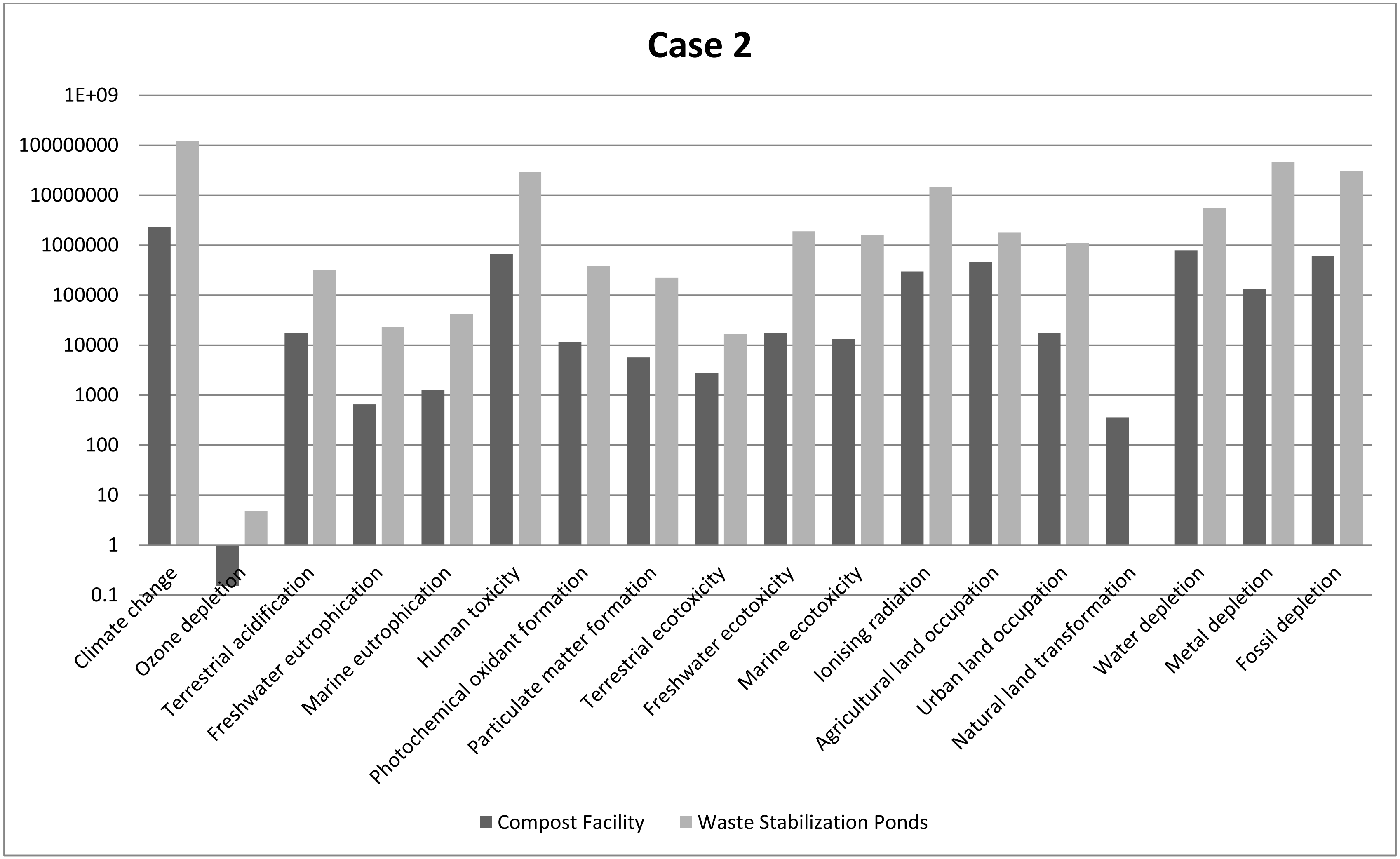

Compost Facility
Fossil depletion
10%
Metal depletion
3%
Water depletion
17%
Agricultural land
occupation
9%
Ionising
radiation
6%
Human toxicity
13%
Climate change
41%


Sewer System
Metal depletion 6%
Fossil depletion 4%
Water depletion 1%
Ionising radiation 2%
Marine ecotoxicity 2%
Climate change 40%
Freshwater ecotoxicity 18%
Marine eutrophication 1%
Human toxicity 25%


Waste Stabilization Ponds
Fossil depletion 12%
Metal depletion 18%
Water depletion 2%
Agricultural land occupation 1%
Ionising radiation 6%
Marine ecotoxicity 1%
Freshwater ecotoxicity 1%
Human toxicity 11%
Climate change 48%

9.3.2 Case 2

Impact category	Unit	Compost Facility	Waste Stabilization Ponds
Climate change	kg CO2 eq	2,325,882.60	123,433,820.00
Ozone depletion	kg CFC-11 eq	0.15	4.89
Terrestrial acidification	kg SO2 eq	17,106.86	324,109.70
Freshwater eutrophication	kg P eq	651.04	23,105.91
Marine eutrophication	kg N eq	1,284.21	41,205.78
Human toxicity	kg 1,4-DB eq	670,535.04	29,267,616.00
Photochemical oxidant formation	kg NMVOC	11,609.95	381,004.29
Particulate matter formation	kg PM10 eq	5,695.83	222,471.16
Terrestrial ecotoxicity	kg 1,4-DB eq	2,815.71	16,741.35
Freshwater ecotoxicity	kg 1,4-DB eq	17,792.79	1,905,707.50
Marine ecotoxicity	kg 1,4-DB eq	13,338.92	1,612,853.30
Ionising radiation	kg U235 eq	299,702.29	14,798,057.00
Agricultural land occupation	m2a	464,263.30	1,785,922.50
Urban land occupation	m2a	17,742.02	1,109,239.50
Natural land transformation	m2	361.87	(2,263.65)
Water depletion	m3	791,729.25	5,535,843.80
Metal depletion	kg Fe eq	132,759.07	46,205,368.00
Fossil depletion	kg oil eq	604,080.47	30,627,423.00


Case 2
1E+09
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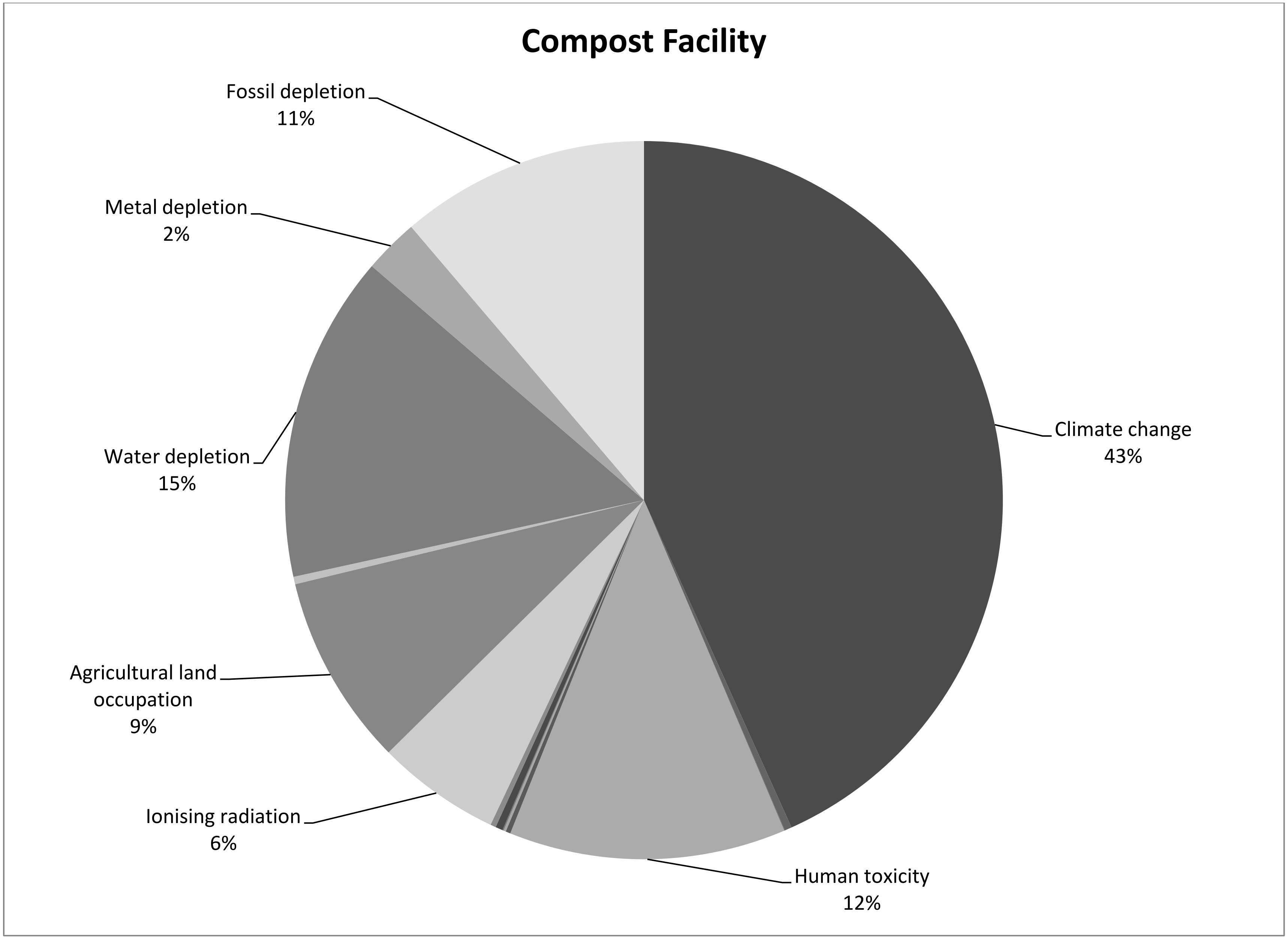
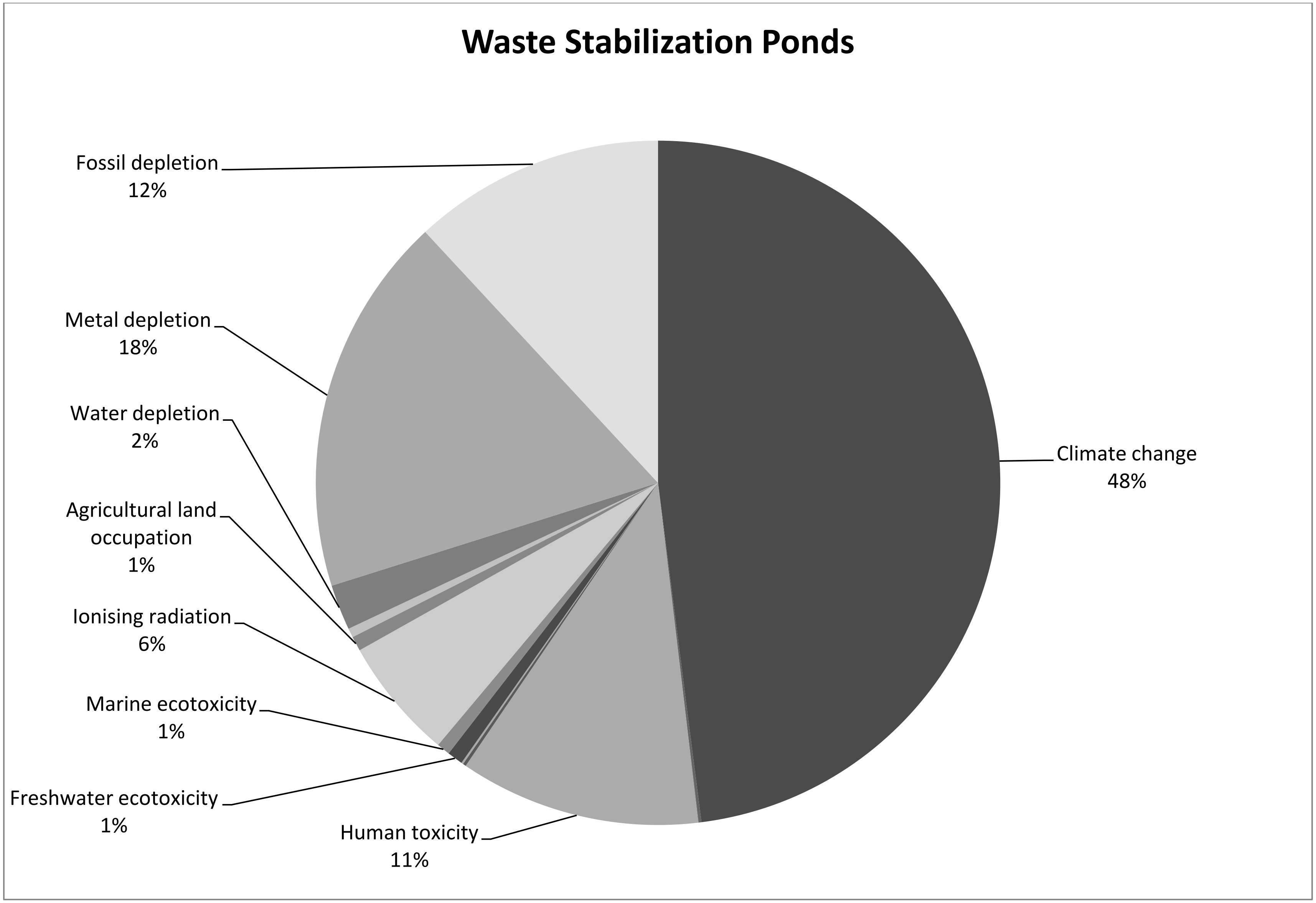
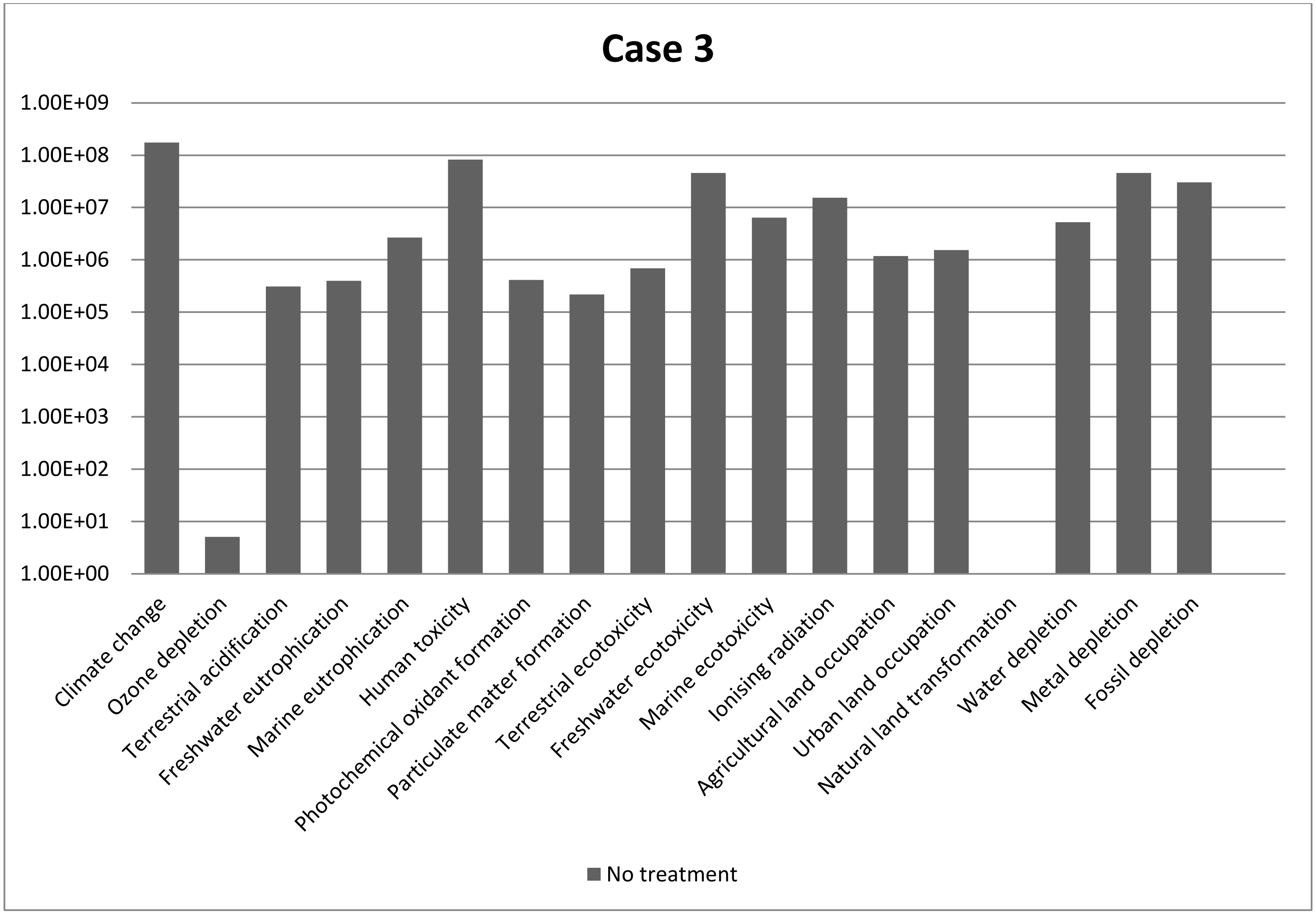
100000
10000
1000
100
10
1
0.1
Climate change
Ozone depletion
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Human toxicity
Photochemical oxidant formation
Particulate matter formation
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Ionising radiation
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion
Metal depletion
Fossil depletion
Compost Facility
Waste Stabilization Ponds


Compost Facility
Fossil depletion 11%
Metal depletion 2%
Water depletion 15%
Agricultural land occupation 9%
Ionising radiation 6%
Human toxicity 12%
Climate change 43%


Waste Stabilization Ponds
Fossil depletion 12%
Metal depletion 18%
Water depletion 2%
Agricultural land occupation 1%
Ionising radiation 6%
Marine ecotoxicity 1%
Freshwater ecotoxicity 1%
Human toxicity 11%
Climate change 48%

9.3.3 Case 3

Impact category	Unit	Do Nothing
Climate change	kg CO2 eq	175,446,560.00
Ozone depletion	kg CFC-11 eq	5.06
Terrestrial acidification	kg SO2 eq	309,295.30
Freshwater eutrophication	kg P eq	395,911.79
Marine eutrophication	kg N eq	2,677,764.30
Human toxicity	kg 1,4-DB eq	82,054,026.00
Photochemical oxidant formation	kg NMVOC	411,915.01
Particulate matter formation	kg PM10 eq	218,900.63
Terrestrial ecotoxicity	kg 1,4-DB eq	687,298.74
Freshwater ecotoxicity	kg 1,4-DB eq	45,472,991.00
Marine ecotoxicity	kg 1,4-DB eq	6,435,595.10
Ionising radiation	kg U235 eq	15,423,781.00
Agricultural land occupation	m2a	1,175,598.50
Urban land occupation	m2a	1,537,114.30
Natural land transformation	m2	(8,416.99)
Water depletion	m3	5,270,876.10
Metal depletion	kg Fe eq	45,636,367.00
Fossil depletion	kg oil eq	30,382,026.00


Case 3
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
Climate change
Ozone depletion
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Human toxicity
Photochemical oxidant formation
Particulate matter formation
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Ionising radiation
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion
Metal depletion
Fossil depletion
No treatment